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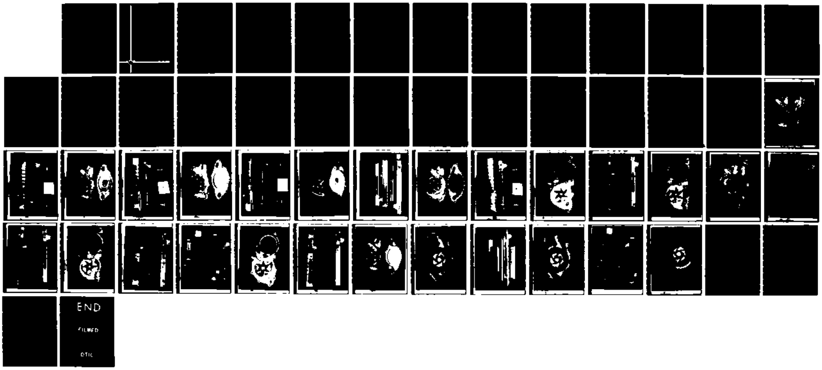

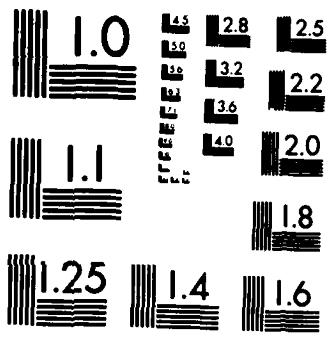

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Report 2415

DEVELOPMENT OF A HIGH-TEMPERATURE COOLANT FOR ADVANCED DIESEL ENGINES

November 1984

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Belvoir R&D Center

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this study was to develop a high-temperature coolant for future advanced military diesel engines capable of operating at high temperatures (up to 150 °C). The desirable coolant for high-temperature application must have a high boiling point, a low freezing point, good thermal properties (specific heat and thermal conductivity) and must be able to protect the various metals of the cooling system and the engine components against corrosion. In order

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to evaluate the candidate coolant for high-temperature application under ~~the~~ laboratory ~~environment~~, the simulated service corrosion test, ASTM D-2570 was conducted at 121 °C for 1064 h. Also with this corrosion test mock-up, the cavitation-corrosion test was performed using an aluminum water pump at 121 °C for 700 h. The antifreezes used in these tests were mixtures of MIL-A-46153 antifreeze and water containing 50, 60, and 80 wt percent ethylene glycol and similar mixtures containing the antifreeze extender additive, MIL-A-53009.

Based on the simulated service test results, the antifreeze mixtures containing 50, 60, and 80 wt percent ethylene glycol with antifreeze extender additive were found to be acceptable as potential candidates for the future advanced diesel engine operating at 121 °C. Among the three candidate coolants, the antifreeze mixture containing 60 wt percent of MIL-A-46153 with antifreeze extender additive proved to be the optimum coolant for high-temperature application (121 °C) based on its boiling point, freezing point, and thermal properties and on the results of the simulated service corrosion and cavitation-corrosion tests. pH and reserve alkalinity.

CONTENTS

TABLES

DEVELOPMENT OF A HIGH-TEMPERATURE COOLANT

FOR ADVANCED DIESEL ENGINES

I. INTRODUCTION

The Army's Advanced Diesel Engine Program includes high-efficiency engines for military vehicles, both the Advanced Diesel (1000 hp) and the Hyperbar engine. With the Advanced Diesel (1000-hp) program, the current effort is to demonstrate 1000 hp from a modified Cummins VT-903 (powerplant for M-2) by applying high-pressure turbo charging, after-cooling, low compression ratio, higher revolutions per minute (3200 vs 2600), and turbo compounding. The other effort involves the Hyperbar which in reality is a gas turbine combined with a diesel engine.[1] It is anticipated that these engines will be operated at higher temperatures (94 to 150 °C) than the currently used, conventional engines which operate at 88 to 94 °C. With these engines, two types of cooling methods are considered, namely air cooling or liquid cooling. At this point, no decision has been made regarding the method of cooling. Since the Materials Fuels and Lubricants Laboratory is responsible for Army coolants, a project was initiated to develop a liquid-coolant for such high-temperature applications.

The desirable characteristics of a high-temperature coolant are to maintain high boiling and low freezing points and good thermal properties (specific heat and thermal conductivity) and to protect the various metals against corrosion, and the coolant must be cost effective and readily available.

In this study, the tests were conducted at 121 °C according to ASTM D-2570, "Simulated Service Corrosion Testing of Engine Coolants" with antifreeze mixtures of MIL-A-46153 antifreeze containing 50, 60, and 80 wt percent ethylene glycol and similar mixtures containing MIL-A-53009, "Additive, Antifreeze Extender, Liquid Cooling System,"[2,3,4] The test temperature of 121 °C was selected because it is the maximum temperature at which the test could safely be conducted with existing components. In addition, aluminum pump cavitation-corrosion tests were conducted at 121 °C.

This report describes the simulated service corrosion test results and how the candidate coolant for operation at 121 °C was selected.

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1 LePera, Maurice E., Trip Report TACOM/MERADCOM Program Interchange, 17 Feb 82.

2 ASTM D-2570, Simulated Service Corrosion Testing of Engine Coolants.

3 Military Specification MIL-A-46153B, "Antifreeze, Ethylene Glycol, Inhibited, Heavy-Duty, Single Package" (31 Jul 79).

4 Military Specification MIL-A-53009, "Additive, Antifreeze Extender, Liquid Cooling System" (6 Aug 82).

II. TEST DETAILS

Laboratory screening tests were conducted according to ASTM Method D-2570. This method evaluates the corrosion occurring on various metal specimens and automotive cooling system components under controlled laboratory conditions. The test temperature specified in this method is 87.8 °C (190 °F). For the purpose of this study, the corrosion tests were performed at 121 °C (250 °F) for 1064 h. This test period is approximately equivalent to 60,000 mi of vehicle field service. The test apparatus is composed of a radiator, water pump, reservoir, electric heater, electric motor, connecting hoses, and temperature measuring and control devices. For safety reasons, the regular connecting hoses were replaced by high-temperature-resistant silicon rubber hoses because of the high test temperature. The metal specimens were prepared according to the ASTM test method.

The antifreeze used in these tests were various solutions in which MIL-A-46153 antifreeze concentrate was diluted with ASTM corrosive water. This MIL-A-46153 is composed of ethylene glycol, corrosion inhibitors, and other additives. In separate solutions, a 3-percent by volume concentration of antifreeze extender (corrosion inhibitor), MIL-A-53009 recently developed by the Materials, Fuels and Lubricants Laboratory was added to the antifreeze. The compositions for each antifreeze are as follows:

Antifreeze	Composition
A	50 percent
B	Antifreeze A plus antifreeze extendeer
C	60 percent
D	Antifreeze C plus antifreeze extender
E	80 percent
F	Antifreeze E plus antifreeze extender

Compositions for Antifreezes A, C, and E are based on weight percent of ethylene glycol in the diluted antifreeze solution. In all solutions, the pH and Reserve Alkalinity (RA) were measured before and after the test by the applicable ASTM methods. In addition to the ASTM D-2570 test, aluminum pump cavitation tests were conducted at 121 °C with Antifreezes B and D for a period of 700 h.

III. RESULTS

Thirteen simulated service corrosion tests were performed with the six antifreezes. Two cavitation-corrosion tests were also conducted with two antifreezes. Table 1 describes the condition of the cooling system components (water pumps and radiators) after the corrosion tests. Their pictures are shown in Appendix C (except of tests 11-13). All water pumps and radiators tested were evaluated in comparison to a new water pump and radiator. In Antifreeze A, three of the four pumps tested (Tests 2, 3, and 4) were found to be corroded on the impeller and on the inside of the pump cover. Two radiators (Tests 2 and 3) were partially clogged around the tube openings. Clogging of the radiator tube is a result of the so-called solder bloom which reduces the heat-transfer capability of the radiator greatly, leading to overheating and loss of coolant. Test 5 conducted with Antifreeze B did not show any visible corrosion on the water pump or radiator. In fact, the pump condition was as good as new and the radiator was very clean.

Table 1. Test Results of the Cooling System Components in ASTM D-2570 Simulated Service Test

Test No.	Antifreeze	Water Pump Condition	Radiator Condition	Radiator Pressure Cap Gasket
1	A	No corrosion.	No deposit; no clogging of tube openings.	Attacked
2	A	Rust on the impeller and inside of the pump cover.	No deposit; partial clogging of tube opening.	Attacked
3	A	Dark spots on the impeller and rust on the inside of pump cover.	No deposit; partial clogging of tube openings	Attacked
4	A	Pitting on the impeller and rust on the inside of pump cover.	No deposit; no clogging.	Attacked
5	B	No corrosion.	No deposit; no clogging.	Attacked
6	C	No corrosion.	Slight deposit; no clogging of tube openings.	Not determined
7[1]	C	Etching of impeller and pitting on the inside of pump cover	First: 691 h Second: 373 h Slight deposit.	Not determined
8	C	Very slight etching on the impeller and slight pitting on the inside of pump cover.	Slight deposit; no clogging of tube openings.	Not determined
9[2]	C	No corrosion.	Partial clogging of tube openings.	Attacked
10	D	No corrosion.	Slight deposit; no clogging of tube openings.	Not determined
11	E	Slight etching of inside pump.	No deposit; no clogging of tube openings.	Not determined

Table 1. Test Results of the Cooling System Components in ASTM D-2570 Simulated Service Test (continued)

Test No.	Antifreeze	Water Pump Condition	Radiator Condition	Radiator Pressure Cap Gasket
12	E	No corrosion.	No deposit; no clogging of tube openings.	Not determined
13	F	Slight deposit; slight pitting of inside pump cover.	Slight deposit of SiO_2 in upper radiator. No clogging of tube opening.	Not determined
14[3]	B	No corrosion. No cavitation. No erosion.	No deposit; no clogging of tube openings.	Attacked
15[3]	D	No corrosion. No cavitation. No erosion.	No deposit; no clogging of tube openings.	Attacked

Notes:

1 After 691 h of operation the radiator was changed because of leakage.

2 The test was terminated after 560 h because of excessive coolant leakage through a broken hose at the inlet of the pump.

3 The cavitation-corrosion tests were conducted using aluminum pumps for 700 h.

With Antifreeze C, two water pumps were corroded. One water pump (in Test No. 7) showed etching on the impeller and pitting on the inside of the pump cover. The other pump (in Test No. 8) showed less etching on the impeller than in Test No. 7. Most radiators remained in good condition except in Test No. 9. It was partially clogged around the tube opening of the radiator similar to those in Tests 2 and 3. Figures 20 and 21 in Appendix C show the water pump and the sectioned radiator used in Test No. 10 with Antifreeze D. There is no evidence of corrosion on the water pump or radiator.

The two simulated service tests (Tests 11 and 12) were conducted with Antifreeze E. One water pump had slight etching of the inside pump cover. The radiators were in good condition.

One corrosion test was performed on Antifreeze F with the antifreeze extender added to Antifreeze E. The water pump was in good condition except for slight pitting of the inside pump cover. The radiator was very clean.

All rubber gaskets of the radiator caps used in these simulated service corrosion tests were attacked by the hot coolant. The deterioration of the gaskets did not maintain a tight seal of the pressure cap because of the changes in the density and increased hardness of the rubber during the testing period. For the rubber gasket failures, most corrosion tests had excessive overflow of coolant from the radiators. These rubber gaskets were originally designed for use at 110 °C (230 °F) and, for this reason, were actually expected to be marginal or unsuitable at 121 °C (250 °F). In follow-up experiments (Tests 4, 6, 10, and 12), the conventional rubber gaskets were replaced with fluoro-rubber gaskets which are designed for high-temperature application. However, no improvement was observed in these tests.

In a similar case, the water pump seals failed in the hot coolant. It was observed that the coolant was leaking through the pump safety hole which was designed to protect the pump-bearing from the coolant. This safety hole is between the water pump seal and pump bearing. Normally, the leakage of the coolant from the pump safety hole represents the failure of the pump seal. These pump seals are also designed for operation at 110 °C (230 °F).

A summary of the average corrosion weight losses of specimens, pH, and RA of the antifreezes tested are shown in Table 2. Their raw data are also presented in Appendix A. These data showed a large scatter with aluminum and solder specimens. The repeatability of this test method is generally poor. In this simulated corrosion test, the degree of corrosion is judged by weight loss of each metal specimen according to ASTM D-3306 standard and by visible corrosion on the water pump, radiator, and connecting hoses. These standards are: Maximum weight loss of 20 mg for copper, brass, steel, and cast iron and 60 mg for solder and aluminum. According to ASTM D-3306 "Ethylene Glycol Base Engine Coolant," these limits apply to the 40 to 70 percent (vol) of ethylene glycol concentrate in water at 87.8 °C (190 °F). The conventional engines are operated at this temperature. The corrosion rate of metal specimens in a coolant usually depends upon the test temperature, concentration of coolant, and testing time. It is logical to expect that the corrosion weight loss of metal specimens determined at 121 °C gives different, most likely, higher values than at 87.8 °C. An attempt was made to determine the maximum weight loss values of the metal specimens that appeared to be acceptable at the test conditions considering all criteria espoused in ASTM D-2570. Based on the data obtained in our simulated service corrosion tests, the range of these values was determined using the maximum Likelihood (ML) Computer Program for the two-parameter Weibull distribution with a 90 peercent confidence limit.[5] The upper confidence limits in the median value (scale parameter) of the Weibull distribution were considered for use as a guideline of acceptable values of weight loss for the individual metal specimens. These values could be used or interpreted as suggested upper limits for future tests. However, they have to be considered preliminary due to the limited data base. The computed acceptable values for the metal specimens are shown in Table 2. The computer output for these values and data used are presented in Appendix B.

[5] Rhee, In-Sik, "Evaluation of the L_{10} Life of Military Greases in Wheel Bearings by Computer Analysis," Belvoir Research and Deveopment Center, Report 2409 (Apr 84).

Table 2. ASTM D-2570 Simulated Service Test Results (at 121 °C)

Antifreeze	Solution Characteristics				Average Weight Loss, mg/specimen					
	pH		Reserve A	inity	Cu	ASTM Solder	Brass	Steel	Cast Iron	Al
	Initial	Final	Initial	Final						
A	7.60	7.38	14.75	10.9	32	112	19	9	1	53
B	8.04	7.8	22.4	19.4	20	30	40	2	3[a]	3[a]
C	7.4	7.07	15.8	15.47	26	68	23	5	1	20
D	7.73	7.45	23.0	23.6	19	25	37	1	3[a]	15[a]
E	6.90	6.65	22.8	20.5	29	571	23	1	2[a]	6
F	7.22	6.99	31.0	29.4	21	65	11	3	2[a]	14[a]
Computed Acceptable Values[b]					40	120	30	10	10	50

[a] Indicates a weight gain.

[b] These were chosen on the basis of the experimental data in this report.

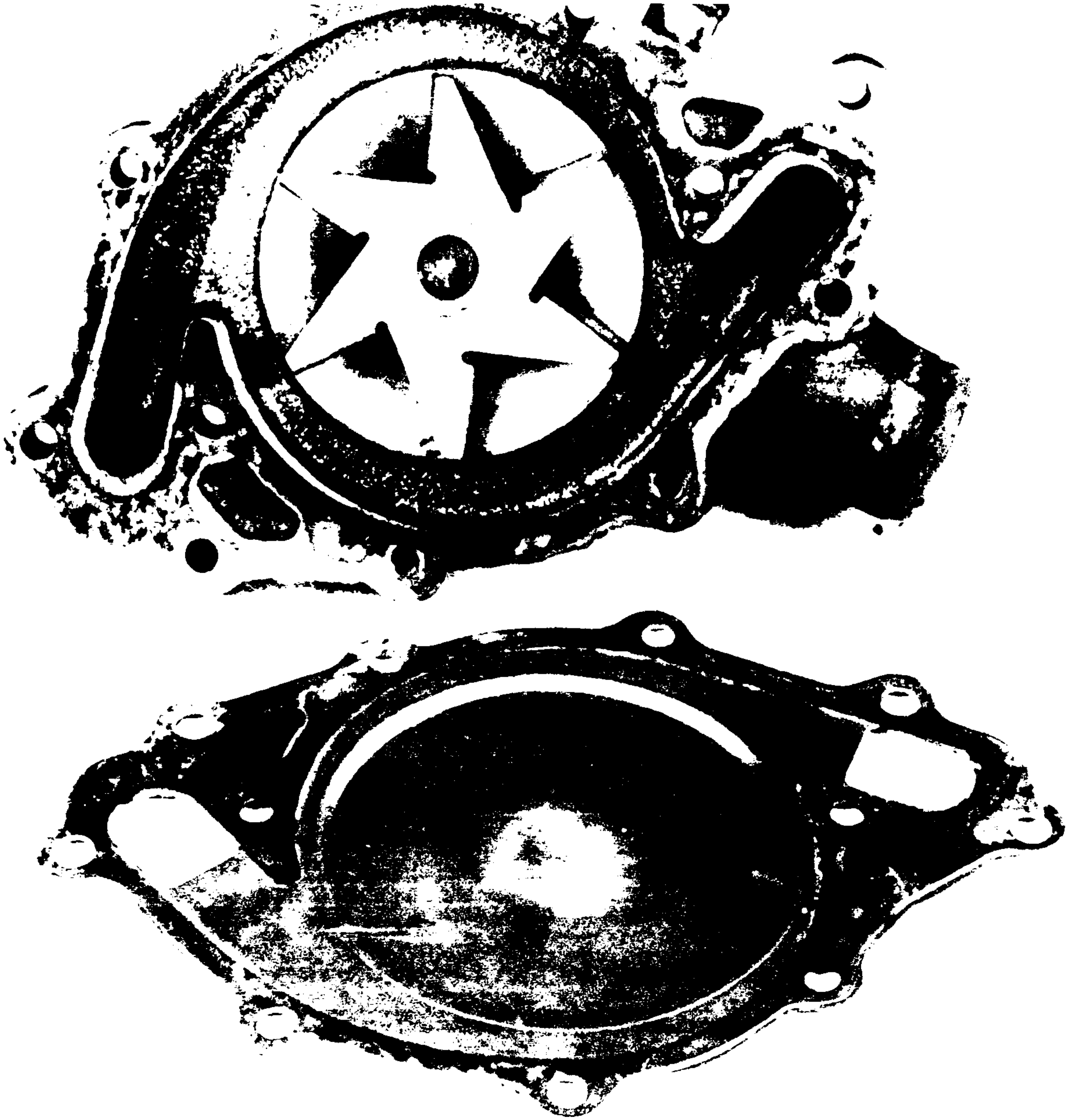

Figure C 1 Test No 1 cast iron pump

APPENDIX C

PHOTOGRAPHS OF DISASSEMBLED PUMPS AND SECTIONED RADIATORS

Table B-2. Summary of Computed Acceptable Values for Metal Specimens

	Cu	ASTM Solder	Brass	Steel	Cast Iron	Al
Upper Limit of Scale Parameter[a]	35.6403	116.5102	25.1174	8.3524	6.7863	44.7415
Computed Acceptable Value[b]	40	120	30	10	10	50
Variance	3.2903	51.2020	1.3502	1.3740	1.3543	38.6407

[a] These values were found on basis of experiment data in this report.

[b] These values were determined as a roundup of upper limit of scale parameter (median value) of Weibull distribution.

Estimated and Two-sided 90 Percent Confidence Intervals for the *Cast-Iron* Specimen

Shape (Beta) Parameter = 1.3328	Scale Parameter = 4.3861
Lower Limit = 0.8854	Lower Limit = 2.8348
Upper Limit = 2.0064	Lower Limit = 2.8348

Estimated Covariance Matrix of Parameter Estimates

	Scale	Shape
Scale	1.3543	0.1288
Shape	0.1288	0.1098

Weight loss data used for this computation:

1	6	12	2	2	4	1	5	3

Estimated and Two-sided 90 Percent Confidence Intervals for the *Aluminum* Specimen

Shape (Beta) Parameter = 1.0713	Scale Parameter = 32.7389
Lower Limit = 0.8357	Lower Limit = 23.9562
Upper Limit = 1.3733	Upper Limit = 44.7415

Estimated Covariance Matrix of Parameter Estimates

	Scale	Shape
Scale	38.6407	0.3257
Shape	0.3257	0.0262

Weight loss data used for this computation:

91	83	98	55	22	35	64	71	70	11	15	16	7	7
10	49	40	28	18	6	16	5	8	6	1	11	17	

Weight loss data used for this computation:

131	142	81	120	108	137	123	112	105	106	105	79	79	62
28	120	96	93	28	57	47							

Estimate and Two-sided 90 Percent Confidence Intervals
for the *Brass* Specimen

Shape (Beta) Parameter = 4.0743
Lower Limit = 3.2348
Upper Limit = 5.1318

Scale Parameter = 23.1247
Lower Limit = 21.901
Upper Limit = 25.1174

Estimated Covariance Matrix of Parameter Estimates

	Scale	Shape
Scale	1.3502	0.2266
Shape	0.2266	0.3266

Weight loss data used for this computationn:

17	15	16	17	20	17	20	17	25	22	20	17	18	16	29	33	33	19
19	25	14	18	18	18	21	24	20	29	28							

Estimate and Two-sided 90 Percent Confidence Intervals
for the *Steel* Specimen

Shape (Beta) Parameter = 1.0606
Lower Limit = 0.8404
Upper Limit = 1.3386

Scale Parameter = 6.0836
Lower Limit = 4.4311
Upper Limit = 8.3524

Estimated Covariance Matrix of Parameter Estimates

	Scale	Shape
Scale	1.3740	0.0592
Shape	0.0592	0.0225

Weight loss data used for this computation:

2	2	1	5	2	2	3	4	10	27	14	10	5	3	5	4	10	3	9
8	2	3	2	2	1	1	1	1										

APPENDIX B

COMPUTED ACCEPTABLE VALUES FOR METAL SPECIMEN WEIGHT LOSS

Table B-1. Computer Output for Calculated Acceptable Values for Metal Specimens

Estimated for the Cumulative Weibull Distribution

$$F(X) = 1 - EXP(-(X/A)\uparrow B)$$

Estimate and Two-sided 90 Percent Confidence Intervals
for thee *Copper* Specimen

Shape (Beta) Parameter = 3.6763	Scale Parameter = 32.5152
Lower Limit = 2.9600	Lower Limit = 29.6642
Upper Limit = 4.5660	Upper Limit = 35.6403

Estimated Covariance Matrix of Parameter Estimates

	Scale	Shape
Scale	3.2903	0.3036
Shape	0.3036	0.2346

Weight loss data used for this computation:

36	34	19	26	20	24	28	29	29	51	40	52	27	25	27
30	28	26	26	22	26	25	25	24	34	31	33			

Estimate and Two-sided 90 Percent Confidence Intervals
for the *ASTM Solder* Specimen

Shape (Beta) Parameter = 3.3123	Scale Parameter = 104.0476
Lower Limit = 2.4442	Lower Limit = 92.9181
Upper Limit = 4.4886	Upper Limit = 116.5102

Estimated Covariance Matrix of Parameter Estimates

	Scale	Shape
Scale	51.2020	1.2509
Shape	1.2509	0.3745

Table A-2. Test Results, pH and Reserve Alkalinity

Test No.	Antifreeze	pH[a] Before Test	pH[a] After Test	Reserve Alkalinity[b] Before Test	Reserve Alkalinity[b] After Test
1	A	7.58	7.54	15.0	12.2
2	A	7.58	7.33	15.0	10.6
3	A	7.58	7.34	15.0	11.2
4	A	7.65	7.29	14.0	9.6
5	B	8.04	7.80	22.4	19.4
6	C	7.40	7.06	15.8	16.0
7	C	7.40	7.05	15.8	15.6
8	C	7.40	7.10	15.8	14.8
9	C (540 h)	7.50	7.08	15.6	20.0
10	D	7.73	7.45	23.0	23.6
11	E	6.90	6.68	22.8	20.8
12	E	6.90	6.62	22.8	20.2
13	F	7.22	6.99	31.0	29.4
14	B (700 h)	8.09	7.91	22.3	20.0
15	D (700 h)	7.91	7.75	25.0	21.2

[a] ASTM D-1287, Test for pH of Engine Antifreezes, Antirusts, and Coolants.

[b] ASTM D-1121, Test for Reserve Alkalinity of Engine Antifreeze, Antirusts, and Coolants.

Table A-1. Test Results, Weight Loss of Metal Specimens, ASTM D-2570 Simulated Service Test (continued)

		Weight Loss, mg/specimen					
Antifreeze	Test No.	Cu	ASTM Solder	Brass	Steel	Cast Iron	Al
F	13—1	20	82	12	2	2[a]	10[a]
	13—2	22	66	14	7	2[a]	21[a]
	13—3	21	48	7	1	1[a]	11[a]
B	14—1[b]	23	26	44	2	1[a]	32[a]
	14—2	26	3[d]	36	1	2[a]	4[a]
	14—3	25	25	45	2	2[a]	1[a]
D	15—1[b]	24	38	43	4	1	11[a]
	15—2	26	30	48	2	0	7[a]
	16—3	25	29	45	2	1[a]	3[a]

Notes:

[a] Indicates a weight gain.

[b] Tests 14 and 15 were the cavitation-erosion test using the aluminum water pump and metal specimens at 121 °C for 700 h.

[c] The steel and cast iron specimen was pitted or rusted.

[d] These values are abnormally high or low. Therefore, these values were excluded for the purpose of calculating an average.

APPENDIX A

TEST RESULTS

Table A-1. Test Results, Weight Loss of Metal Specimens, ASTM D-2570 Simulated Service Test

		Weight Loss, mg/specimen					
Antifreeze	Test No.	Cu	ASTM Solder	Brass	Steel	Cast Iron	Al
A	1—1	36	131	17	2	1[a]	91
	1—2	34	142	15	2	0	83
	1—3	19	81	16	1	2[a]	98
	2—1	26	120	17	5[c]	1[a]	55
	2—2	20	108	20	22	0	22
	2—3	24	137	17	3	1[a]	35
	3—1	28	123	25	4[c]	0	64
	3—2	29	112	22	10[c]	0	71
	3—3	29	105	20	27[c]	1[a]	70
	4—1	51	106	17	14	1	11
	4—2	40	105	18	10	6[c]	15
	4—3	52	79	16	5[c]	12[c]	16
B	5—1	20	41	41	2	3[a]	3[a]
	5—2	22	24	265[d]	2	3[a]	2[a]
	5—3	19	26	39	1	3[a]	4[a]
	6—1	27	79	29	3	2	7
	6—2	25	62	33	5	2	7
	6—3	27	28	33	4	4	10
C	7—1	30	120	19	10	1	49
	7—2	28	96	19	3	1[a]	40
	7—3	26	93	25	9	5	28
	8—1	26	28	14	8	0	18
	8—2	22	57	18	2	2[a]	6
	8—3	26	47	18	3	3	16
D	10—1	19	30	35	0	3[a]	17[a]
	10—2	18	26	37	1	2[a]	15[a]
	10—3	20	19	38	1	2[a]	14[a]
E	11—1	25	756	18	2	2[a]	5
	11—2	25	817	21	2	0	8
	11—3	24	746	24	1	2[a]	6
	12—1	34	483	20	1	2[a]	1
	12—2	31	279	29	1	2[a]	11
	12—3	33	346	28	1	5[a]	17

The radiator pressure cap gaskets and water pump seals were attacked by the antifreezes at 121 °C. Any liquid cooling system operating at 121 °C will require substitution of the previously used materials with elastomers compatible with antifreeze mixtures at high temperature.

The computed acceptable values for metal specimen weight losses are derived from a limited data base, and additional tests would be required to increase the confidence in these values. Results clearly show that specimen weight losses and their acceptability in terms of other criteria are directly correlated to operating conditions. Also, pH and RA of the antifreezes have marked effects on the corrosion of materials and antifreezes, and further study of this interrelation would be beneficial for future formulation of antifreezes for special applications.

Finally, any antifreeze selected for high-temperature applications under a laboratory environment must be certified by engine dynanometer and fleet tests before introduction into the field.

Antifreezes C and E gave moderate weight losses on all metals. The solder in Antifreeze E and the water pumps were slightly corroded. In all tests, the pH and RA changed slightly. According to ASTM and SAE, the pH and RA are not sufficient criterion to indicate the efficiency of corrosion inhibitors.[6, 8, 9] However, they have been used for the Army's antifreeze quite successfully. Evidently, the simulated service corrosion test results showed that the corrosion of all metal specimens, except brass and cooling components was significantly reduced by increasing the RA and pH as a result of adding the antifreeze extender (Antifreeze A vs B, C vs D, and E vs F). This antifreeze extender is composed of sodium metaborate, sodium mercaptabenzothiazole, potassium silicate, and distilled water.

Based strictly on the simulated service test results, the rankings of the antifreezes are as follows:

Ranking	1	2	3	4	5	6
Antifreeze	D	B	F	C	E	A

In order to select the best coolant for operation at 121 °C, all critical criteria including the physical properties of the coolant must be considered. Antifreeze F has the highest boiling point but the specific heat and thermal conductivity are less than Antifreezes D and B. Antifreeze F also has the lowest freezing point, but with loss of water the freezing point rises and the thermal properties decreases further. Antifreeze B has good thermal properties and a fairly low freezing point; its boiling point is the lowest of the three best mixtures. Antifreeze D has better thermal properties than does Antifreeze F but lower ones than Antifreeze B. It has a higher boiling point than does Antifreeze A but lower than Antifreeze F. The freezing point of Antifreeze D is lower than that of Antifreeze D and with loss of water, it would be even lower.

V. CONCLUSIONS

It is concluded that: From simulated service corrosion test results, Antifreezes B, D, and F can be considered as potential candidates for a future advanced diesel engine operating at 121 °C. Among the three candidate coolants, Antifreeze D is clearly the optimum coolant for high-temperature application at 121 °C based on its boiling point, freezing point, thermal properties, and the results of the simulated service and cavitation-corrosion tests performed under the laboratory environment. This antifreeze mixture consists of 60 weight percent ethylene glycol diluted with ASTM corrosive water plus a 3 percent by volume addition of MIL-A-53009 antifreeze extender additive.

Antifreeze A having a similar composition as the conventional optimum coolant (50/50 Vol percent ethylene glycol/water solution), based on the corrosion test results, is not suitable for high-temperature applications at 121 °C. Antifreezes C and F performed better than did Antifreeze A, but they also do not meet our high-temperature coolant criteria.

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6 SAE Handbook, Volume I, Materials, "Engine Coolants—SAE J814C," (1983).

8 ASTM D-1287, Test for pH of Engine Antifreezes, Antirusts, and Coolant.

9 ASTM D-1121, Test for Reserve Alkalinity of Engine Antifreeze, Antirusts, and Coolant.

Table 4. Physical Properties of Aqueous Ethylene Glycol Solutions

Antifreeze	% by wt	% by vol	Boiling Point °C at 2 Atm	Freezing Point (°C)	Specific Heat at 121 °C cal/g/°C	Thermal Conductivity cal-cm/sec/cm²/°C at 121 °C
A, B	50	47.8	129	-36	0.887	0.00096
C, D	60	58.0	132	below -48	0.852	0.00085
E, F	80	78.9	143	-47	0.762	0.00066
	90	89.4	—	-29	0.721	0.00059

From Table 4, it is obvious that as the boiling point increases, the concentration of ethylene glycol is increased. The freezing point decreases, reaches the eutectic point, and then increases again as the concentration increases. The specific heat and thermal conductivity decrease continually as the concentration of ethylene glycol increases. Therefore, the ideal solution is in the range of 60 percent. By increasing the system pressure, a higher boiling point can be obtained, and by providing the system with the proper flow rate and appropriately sized radiator, any desired bulk temperature can be maintained. The test temperature of 121 °C was selected as the maximum safe temperature that could be used with the existing test equipment.

The simulated service corrosion test results at 121 °C indicate that metal corrosion varies with concentration, pH, and RA. Other factors affecting the test results were the temperature effect on the pressure cap and pump seals. Based on simulated service corrosion test results, Antifreeze D exhibited the lowest specimen weight losses on all metals except brass. Although Antifreeze D gave higher brass weight losses than its calculated acceptable value, there was no adverse effect on the radiator which is all brass with solder joints. This result clearly shows that this value is too low to use as the criterion of brass specimen weight loss for those tests containing the extender. All pumps and radiators were clean. In addition, the cavitation-corrosion tests conducted with two antifreeze concentrations (50 and 60 percent) showed no cavitation or corrosion of the aluminum pumps and no corrosion on the radiators. Therefore, it is concluded that for almost all tested antifreezes containing extender, including Antifreeze D, the acceptable values for brass weight loss are at least as high as the ones actually observed in the individual tests, since none of the componens showed any signs of corrosion. The results of the test with Antifreeze B were similar to the results of Antifreeze D.

Even though the test with Antifreeze F showed the lowest brass weight losses among the antifreezes tested, it showed significantly higher solder weight losses as compared with Antifreezes B and D. Antifreeze A had higher weight losses on the copper, solder, aluminum, and steel specimens. Three out of the four pumps were corroded, and the steel and cast iron specimens were pitted and rusted. Solder bloom was found in the radiators. Although considered to be an excellent coolant for the Army, and with many years of satisfactory service in vehicles that operate in the 88 to 94 °C range, this antifreeze mixture cannot be considered satisfactory at the higher temperature of 121 °C (250 °F) according to these test results.

Table 3. Cavitation-Corrosion Test Results

Antifreeze	pH		Reserve Alkalinity		Average Weight Loss, mg/specimen					
	Initial	Final	Initial	Final	Cu	ASTM Solder	Brass	Steel	Cast Iron	Al
B	8.09	7.91	22.3	20.0	25	26	42	2	2*	9*
D	7.91	7.75	25.0	21.2	25	32	45	3	0	7*

*Indicates weight gain.

From Table 2, it is evident that most metal specimens passed the computed acceptable values except aluminum for Antifreeze A, brass for Antifreezes B and D, and solder for Antifreeze E. In our observation, the antifreeze extender did not prevent the corrosion of brass specimens. Evidently, Antifreeze B gave higher brass weight loss than Antifreeze A. Antifreeze D had similar results as Antifreeze B. Antifreeze E showed the highest weight loss for solder among the antifreezes. It appears that the solder specimens were attacked due to the acidity of the solution. Obviously, the value of pH in Antifreeze E changed from 6.9 to 6.6. By visual inspection, it was found that 5 out of 12 steel specimens and 2 out of 12 cast iron specimens were pitted and rusted in Antifreeze A (Tests 2, 3, and 4). This corrosion showed not only on the specimens but also on the water pumps. The pH and reserve alkalinity of the antifreezes were measured before and after the tests. The results are shown in Table 2. They changed slightly during the testing period. The cavitation-corrosion tests were conducted using aluminum water pumps. The antifreezes used in these tests were Antifreezes B and D. The test results are shown in Figure 23 to 26 (Appendix C) with a new aluminum pump in Figure 27 (Appendix C). The corrosion test results are presented in Table 3.

There is no cavitation-corrosion occurring on the aluminum water pumps. The pumps conditions were as good as new. The weight loss of metal specimens showed similar results in comparison with the corrosion test at 1068 h. The radiators were in excellent condition. In our observation, the antifreeze extender (inhibitor) provided superior corrosion protection on the aluminum water pumps and the aluminum and solder specimens.

IV. DISCUSSION

For an engine coolant to be effective, it must be able to do several things. It must be capable of transferring heat from the engine and maintain a given bulk fluid temperature. The boiling point must be high enough to prevent boiling in the system both during operation and immediately after the engine is stopped. It must be able to maintain a low freezing point for cold weather operation, and it must afford corrosion protection to all cooling system metals and components. Inhibited ethylene glycol-water-solutions are the most widely used coolants for engine cooling systems. The Army has used ethylene glycol-based coolants for many decades. Physical properties of aquaeous solutions of ethylene glycol are given in Table 4.[6] [7]

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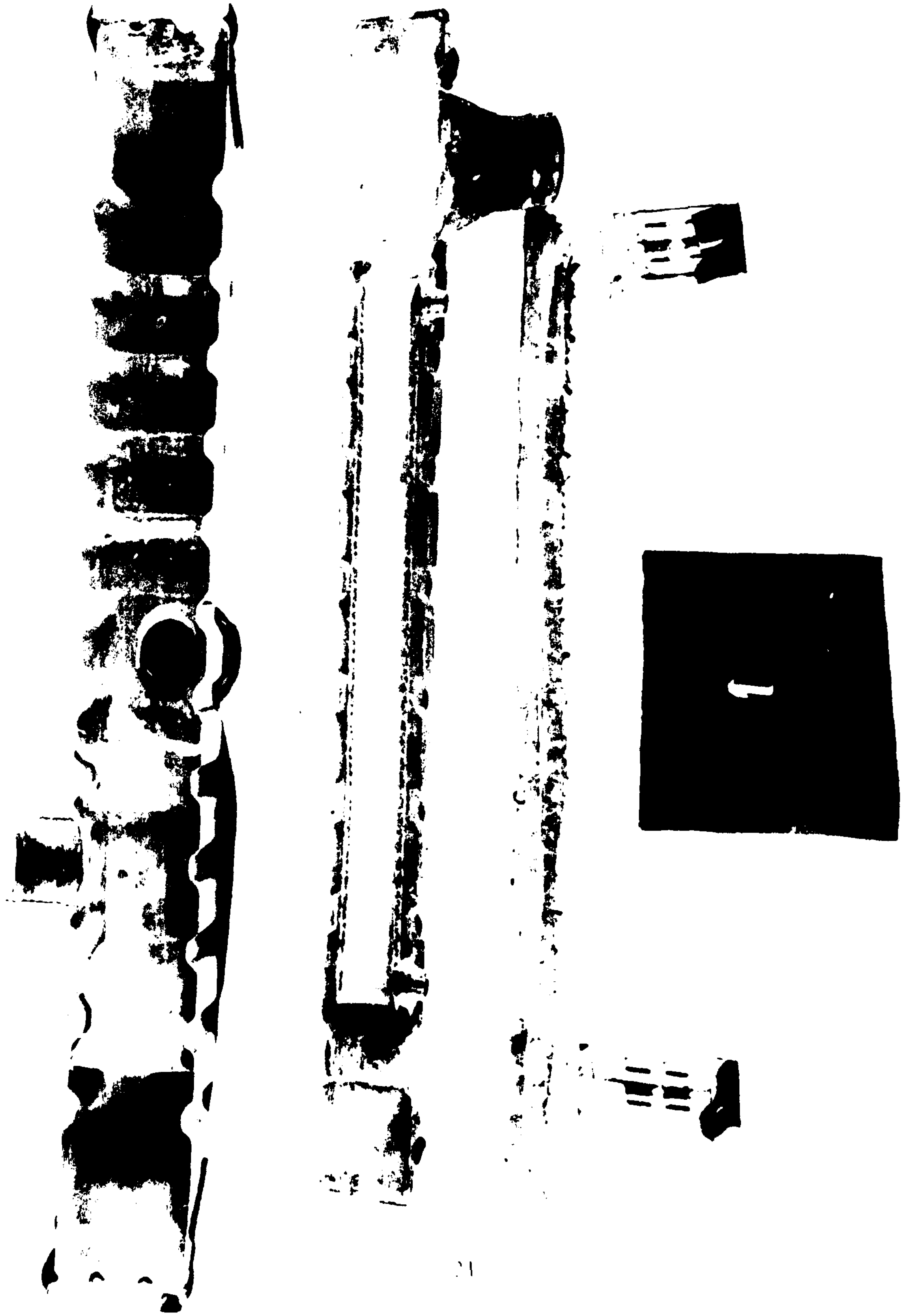
[6] SAE Handbook Volume I. Materials, "Engine Coolants—SAE J814C" (1983).

[7] Curme, George O. and Johnston, Franklin, "Glycols," pages 40 to 55, Reinhold Publishing Corporation (1952).



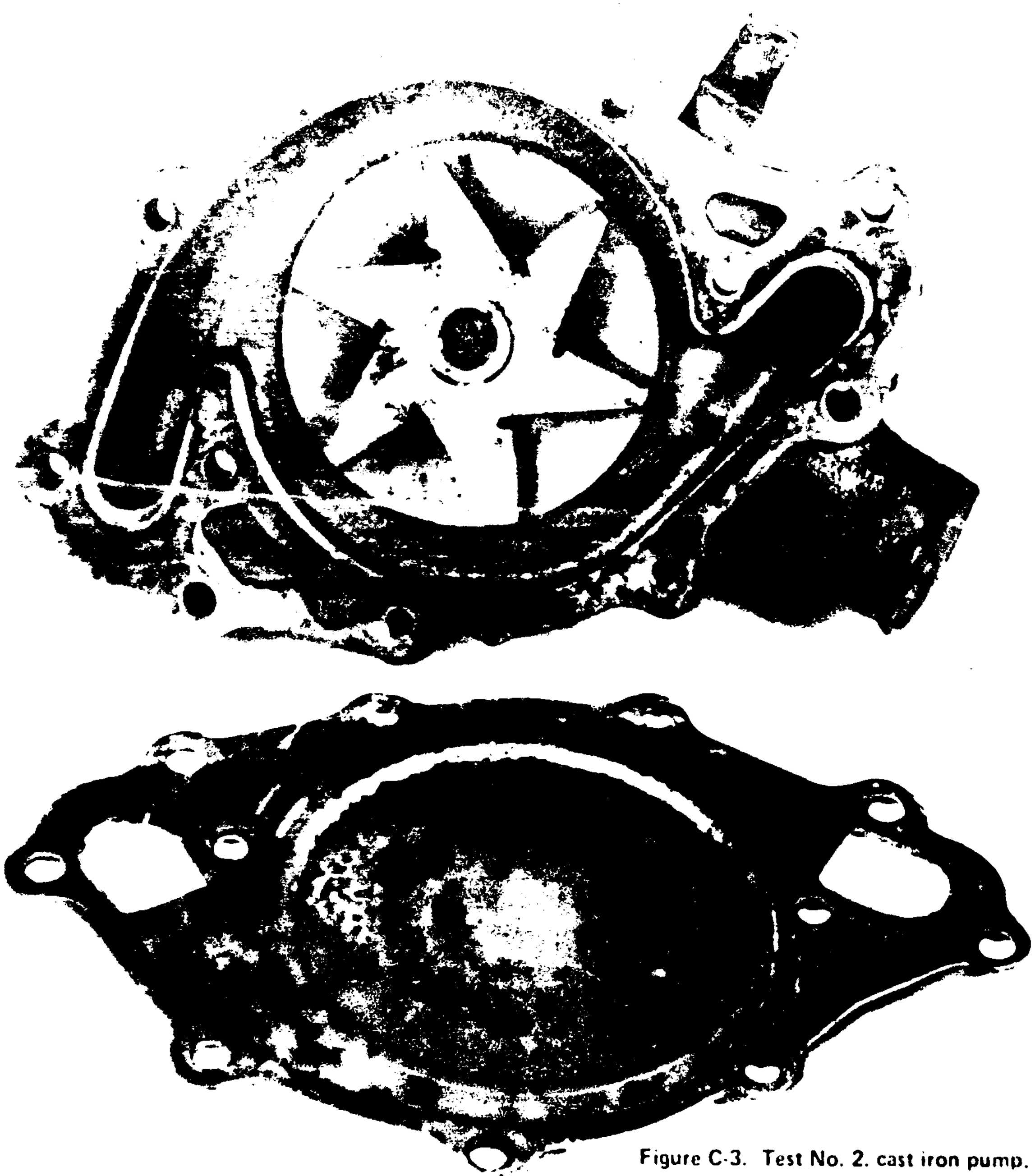


Figure C-3. Test No. 2. cast iron pump.

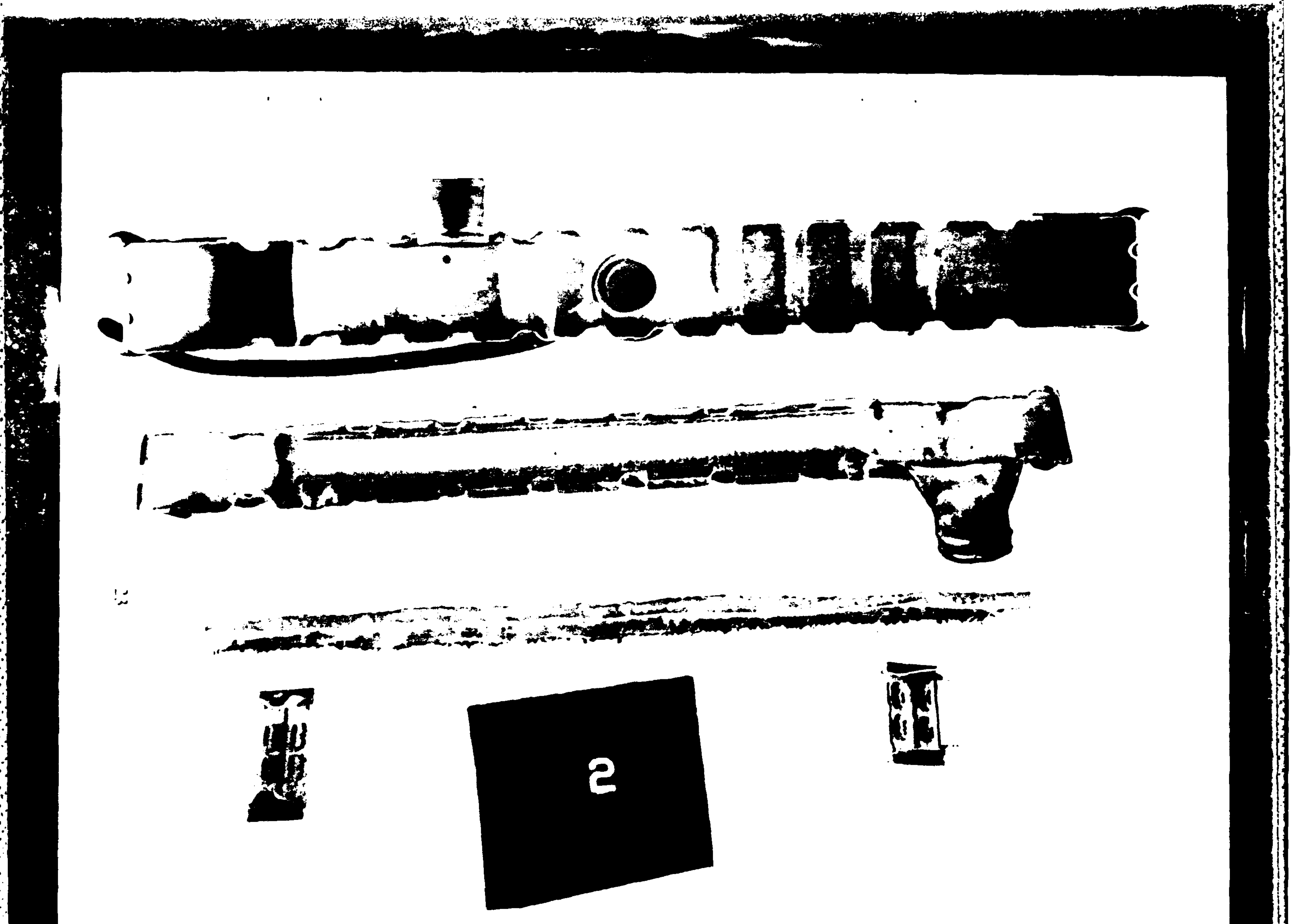


Figure C-4. Test No. 2. radiator's components.

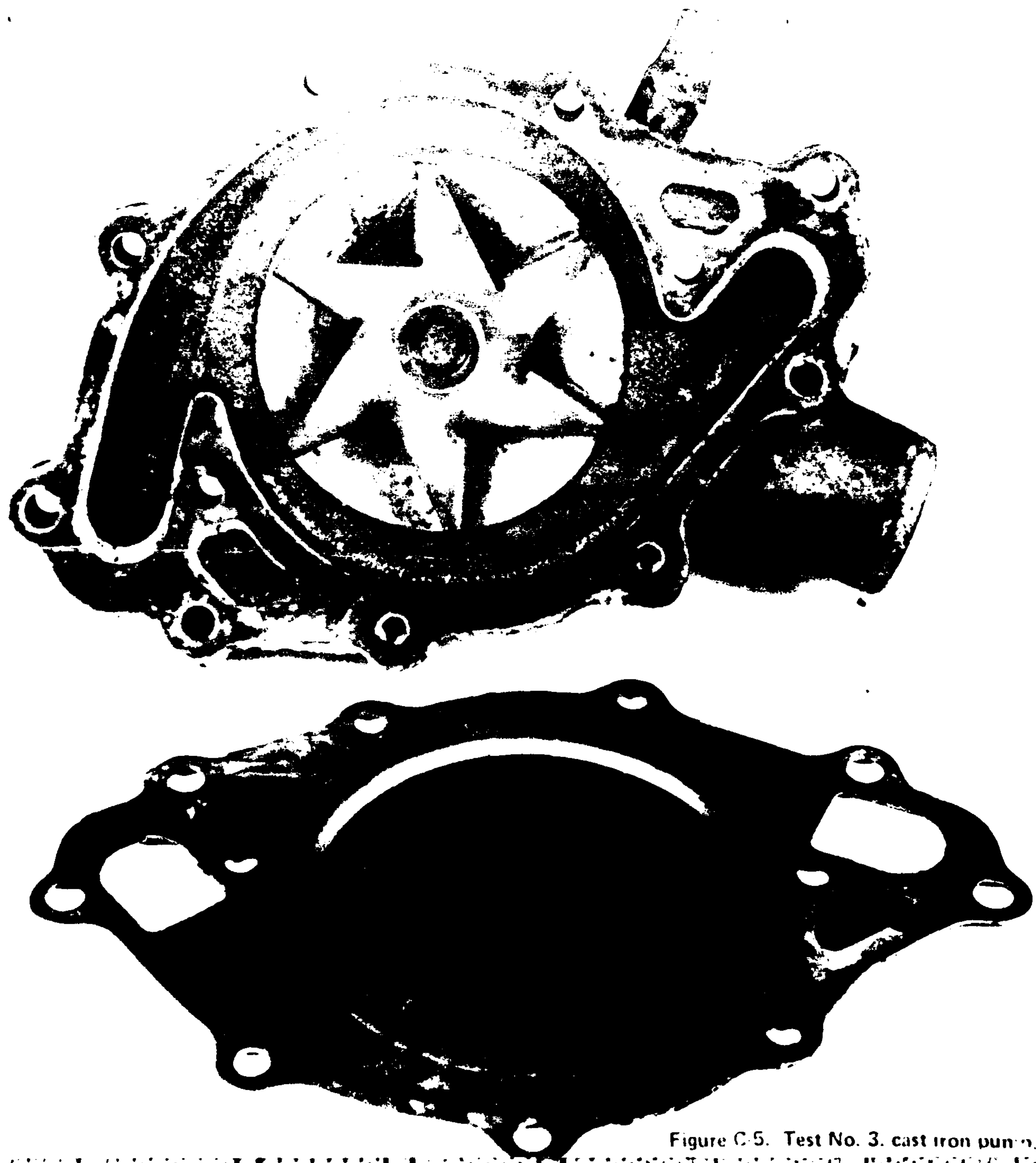


Figure C-5. Test No. 3, cast iron pump.

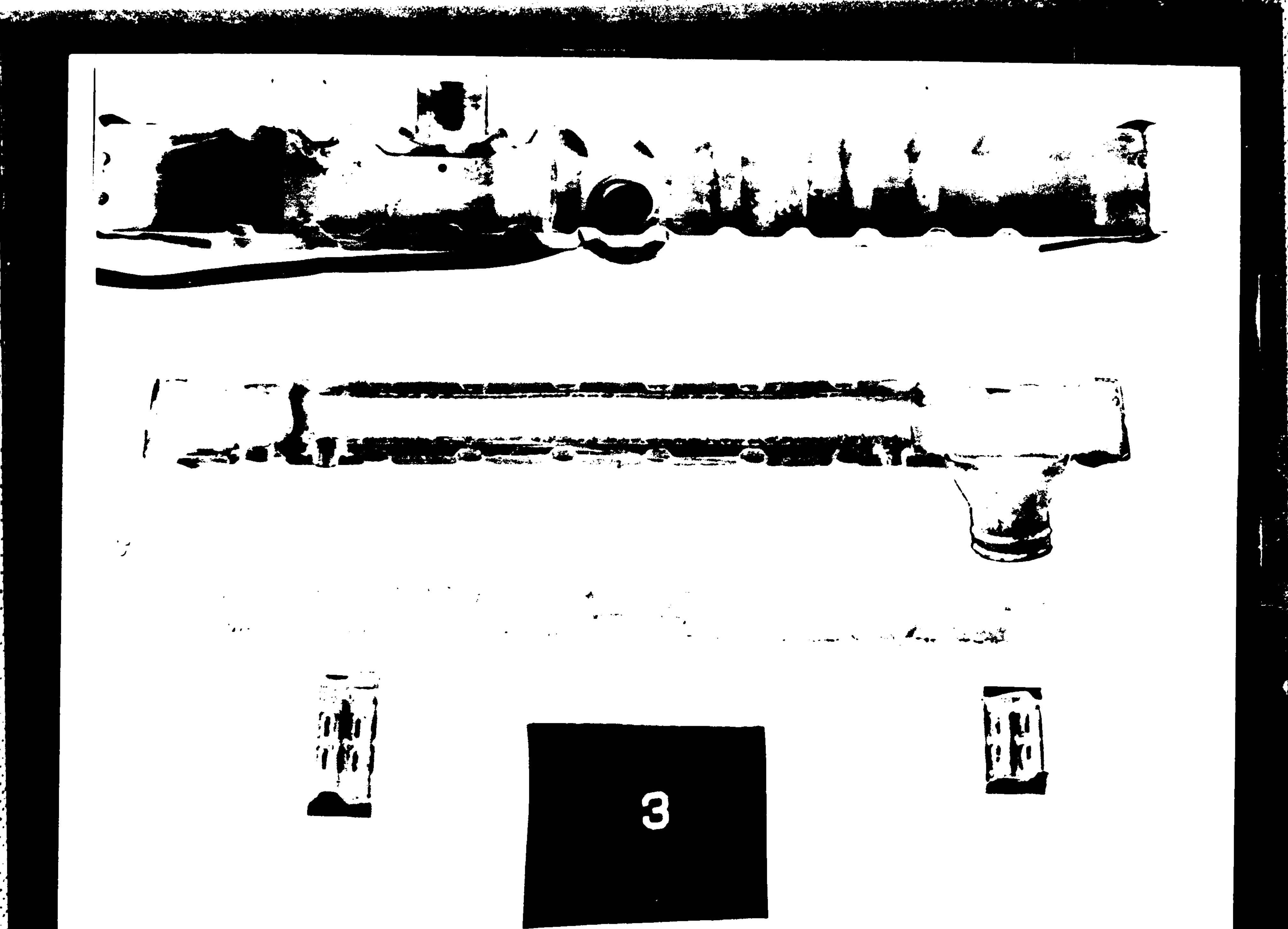


Figure C-6. Test No. 3. radiator's components.

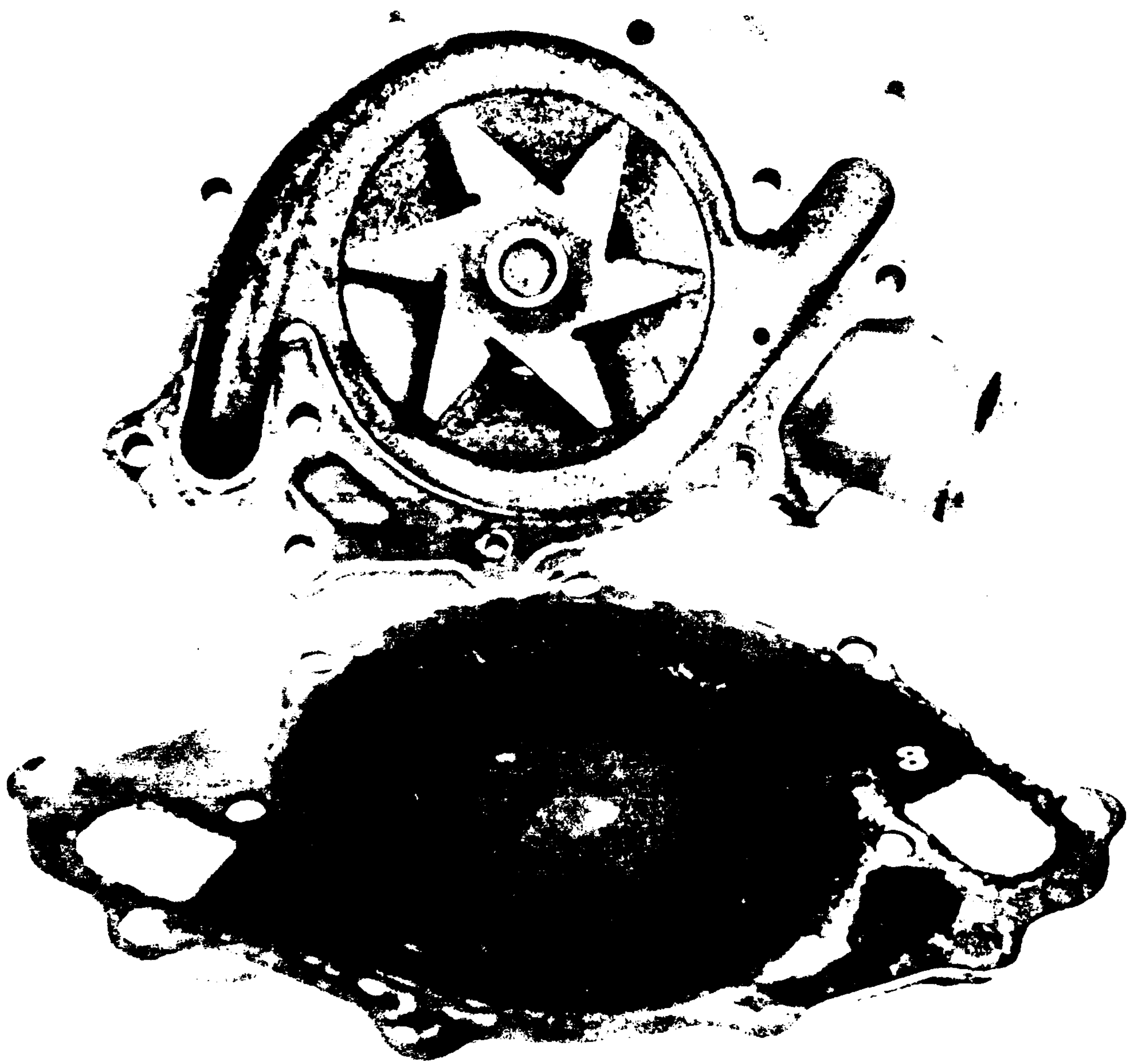


Figure C-7. Test No. 4. cast iron pump.

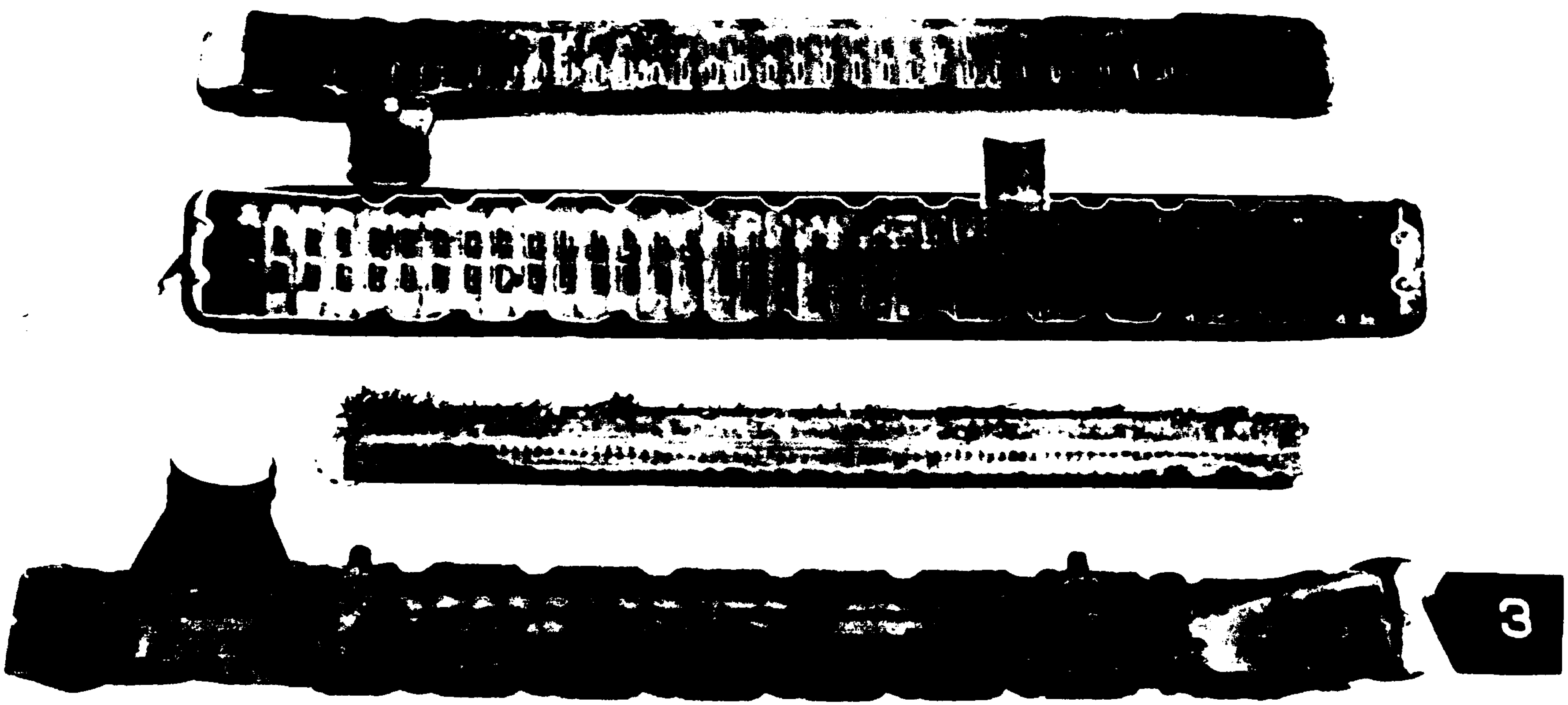


Figure C-8. Test No. 4, radiator's components.

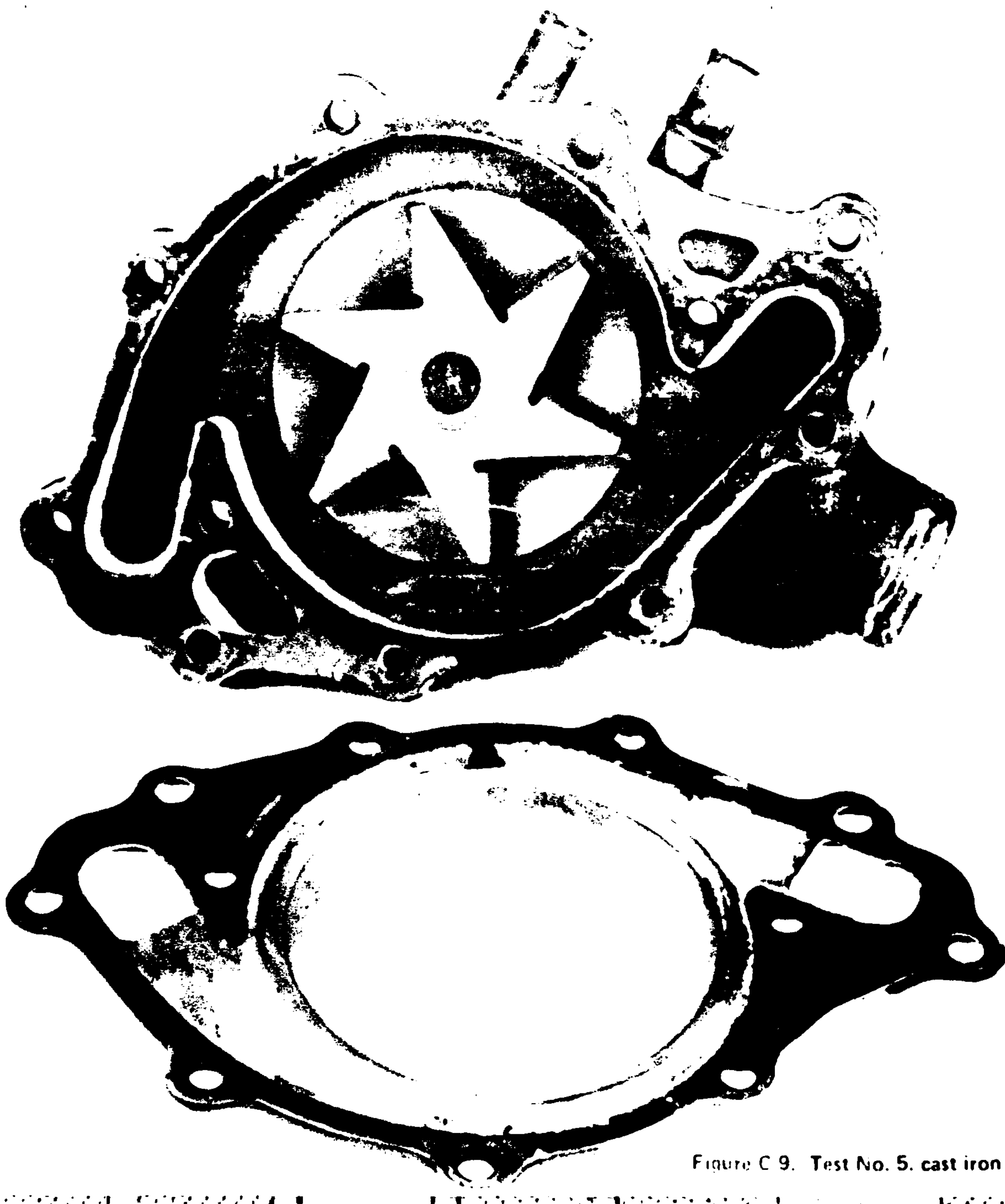


Figure C 9. Test No. 5. cast iron pump.

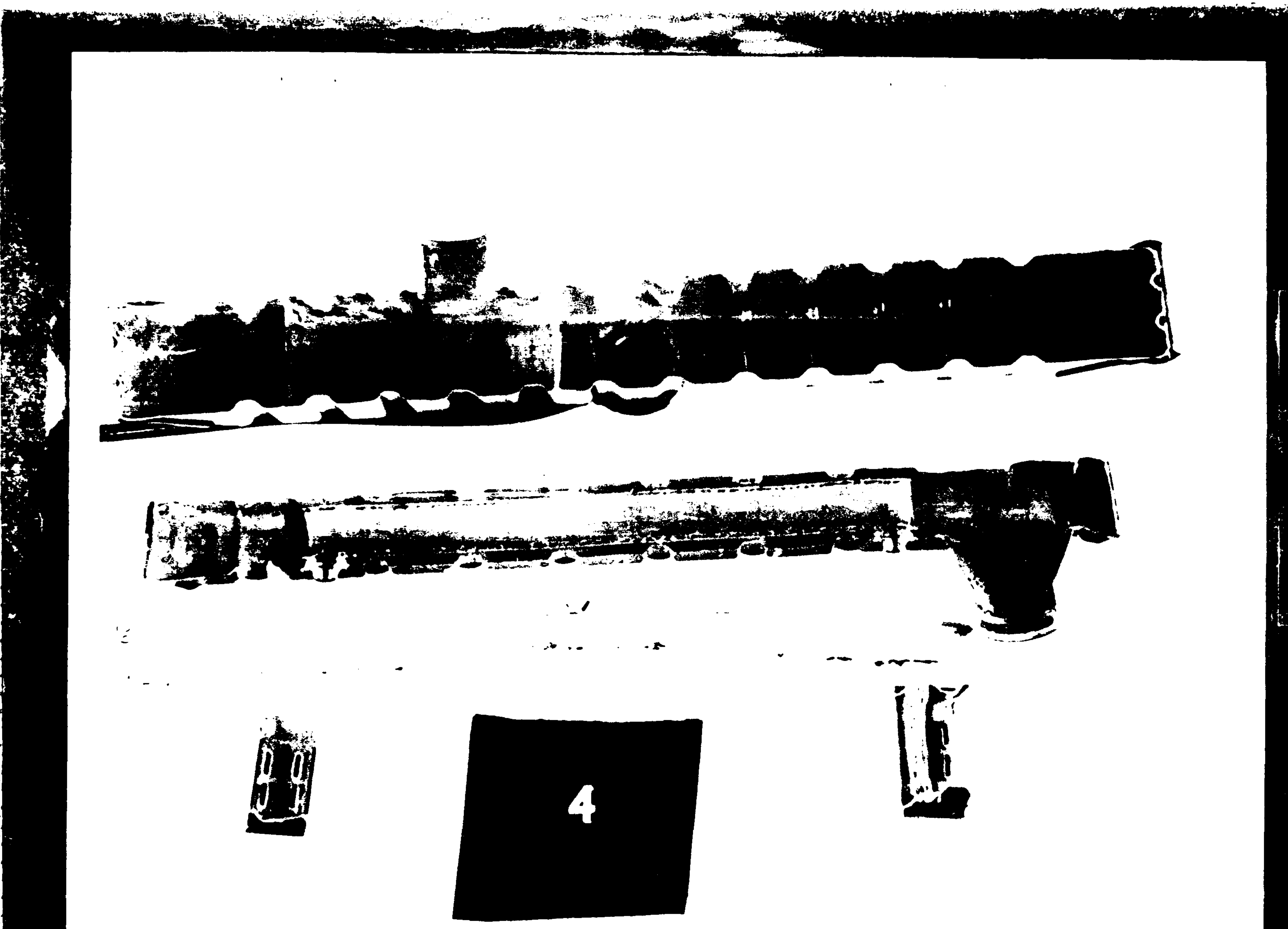


Figure C 10. Test No. 5 radiator's components.

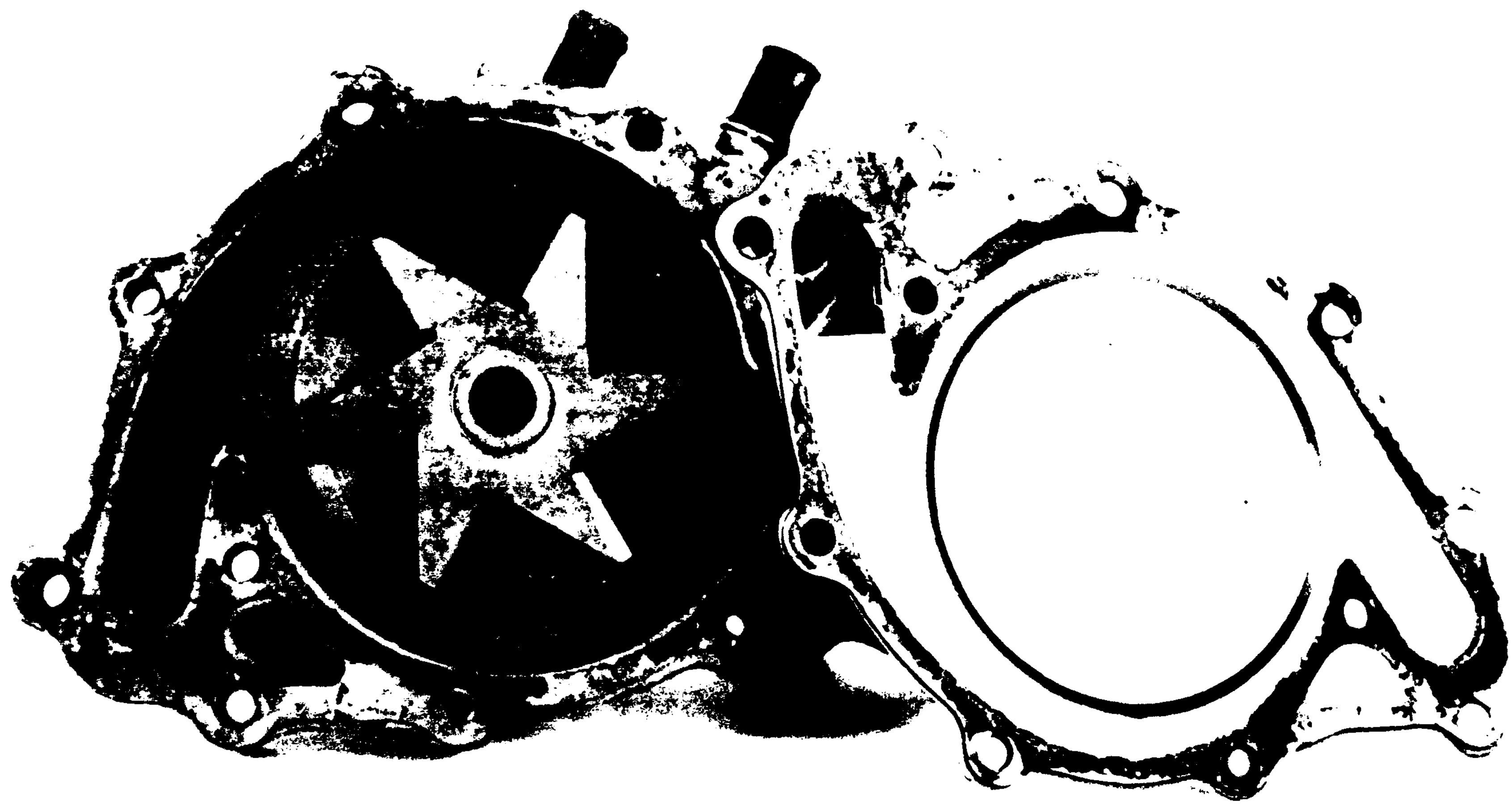


Figure C-11. Test No. 6. cast iron pump.

1

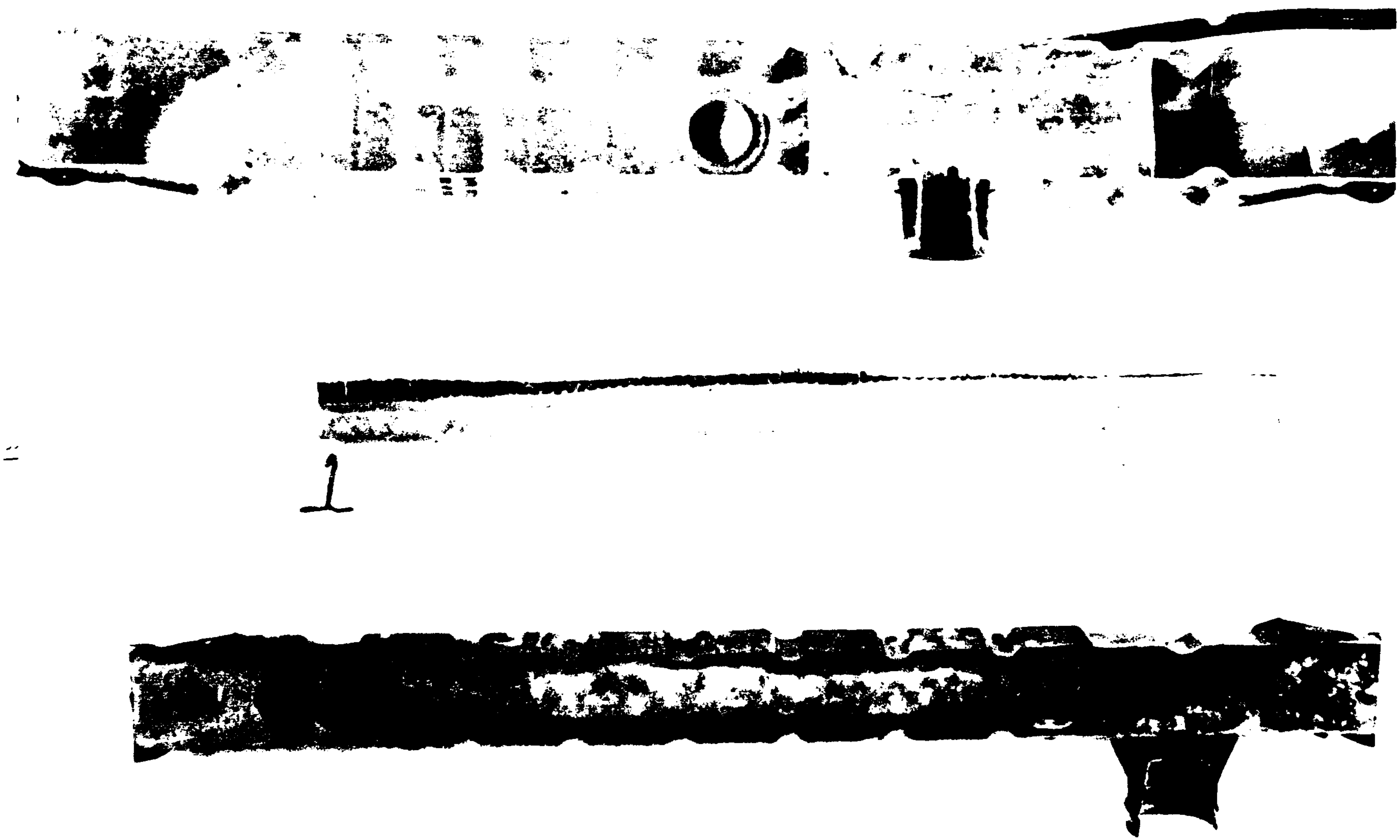


Figure C-12. Test No 6. radiator's components.

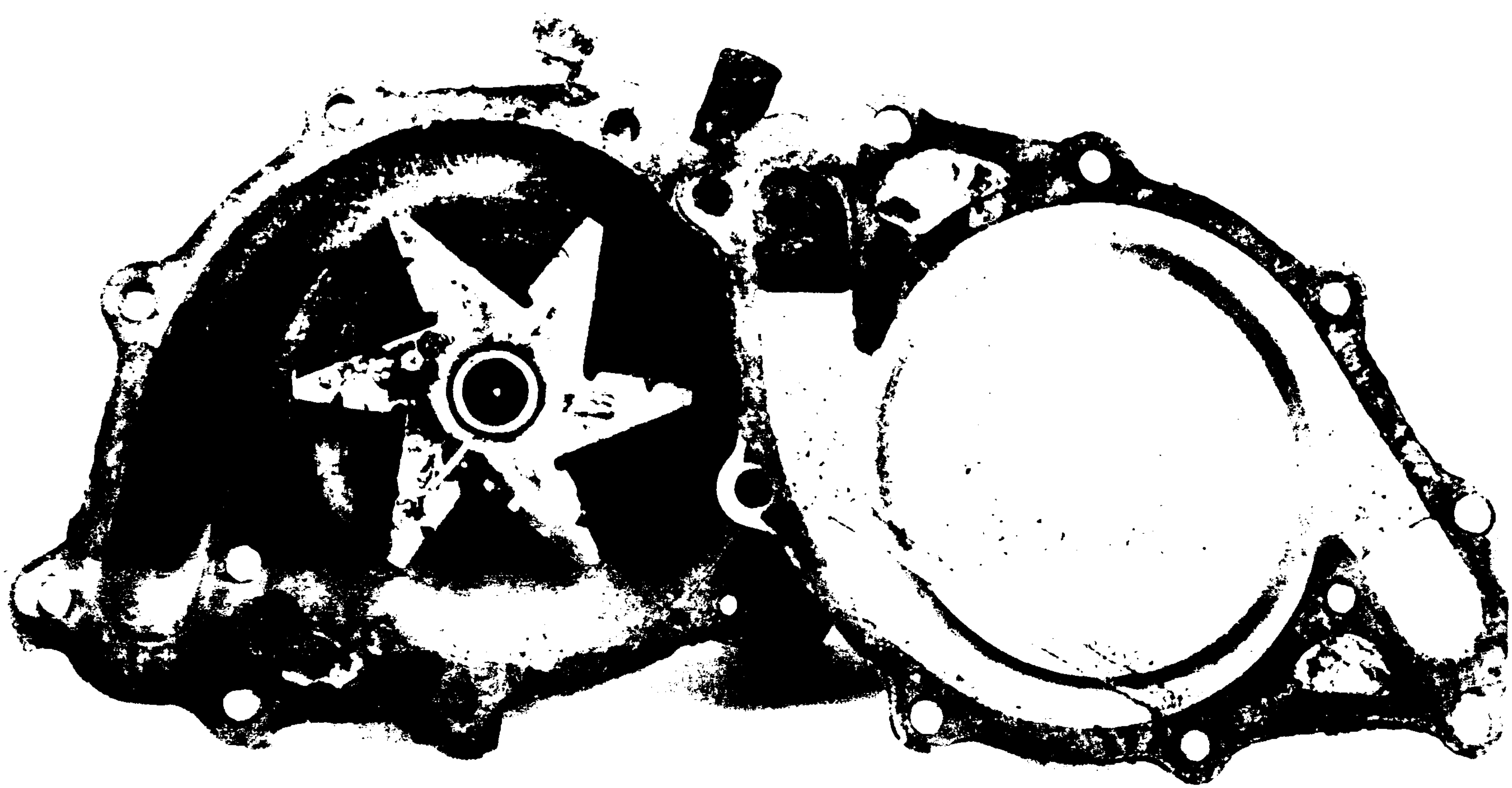


Figure C-13. Test No. 7. cast iron pump.

2

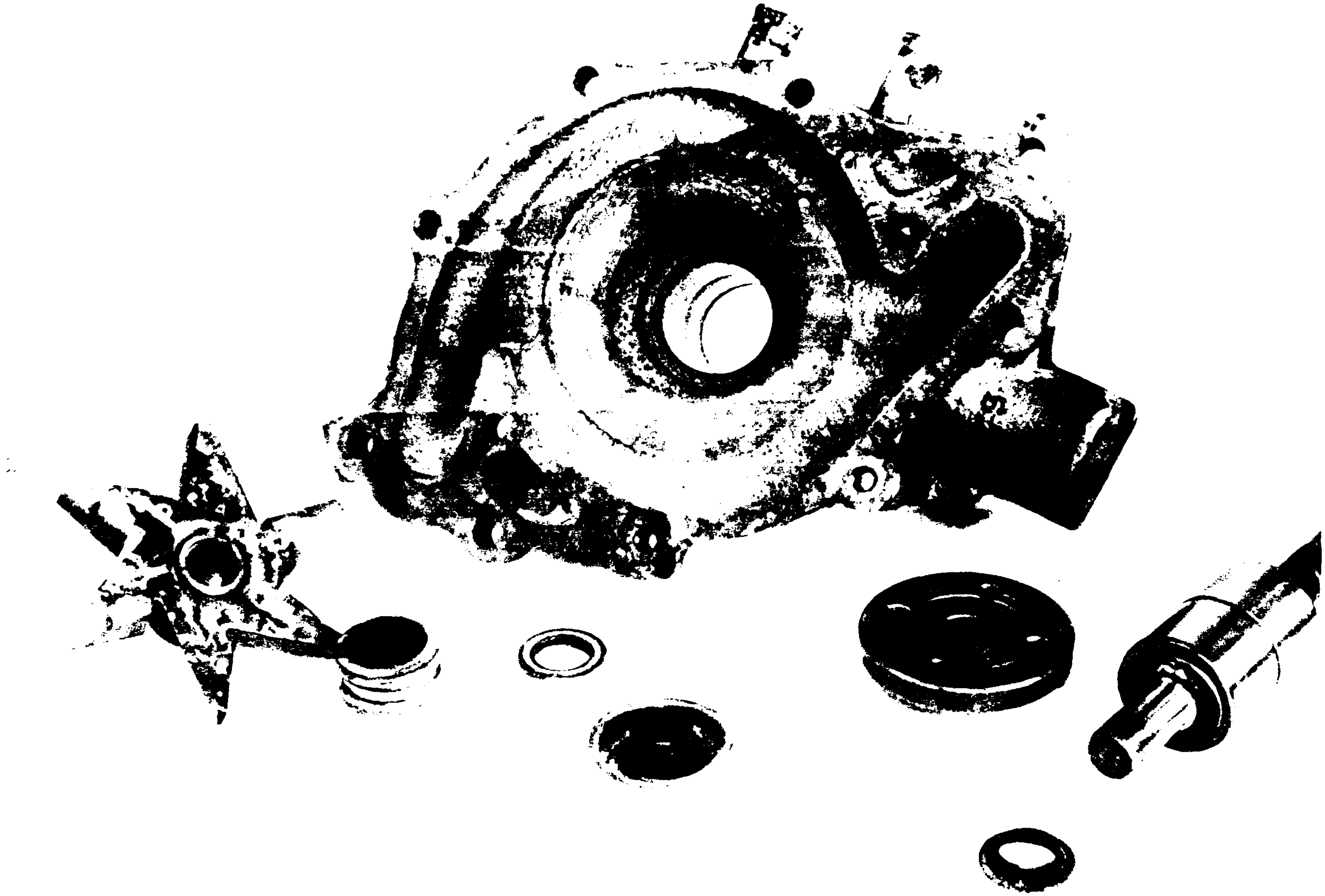


Figure C-14 Test No. 7 cast iron pump, disassembled.

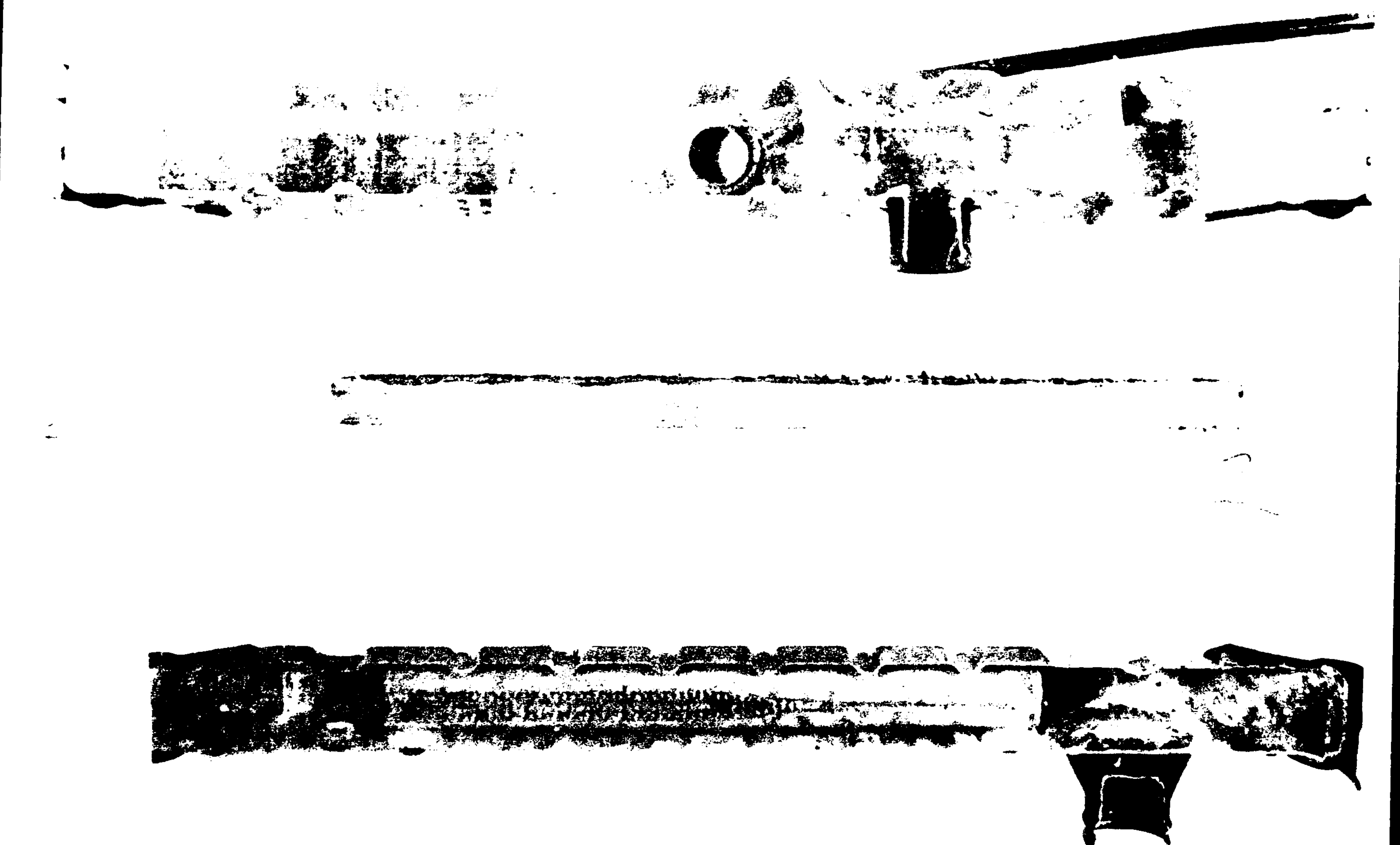


Figure C-15. Test No. 7. radiator's components, after 691 h.

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Figure C-27. New aluminum water pump.

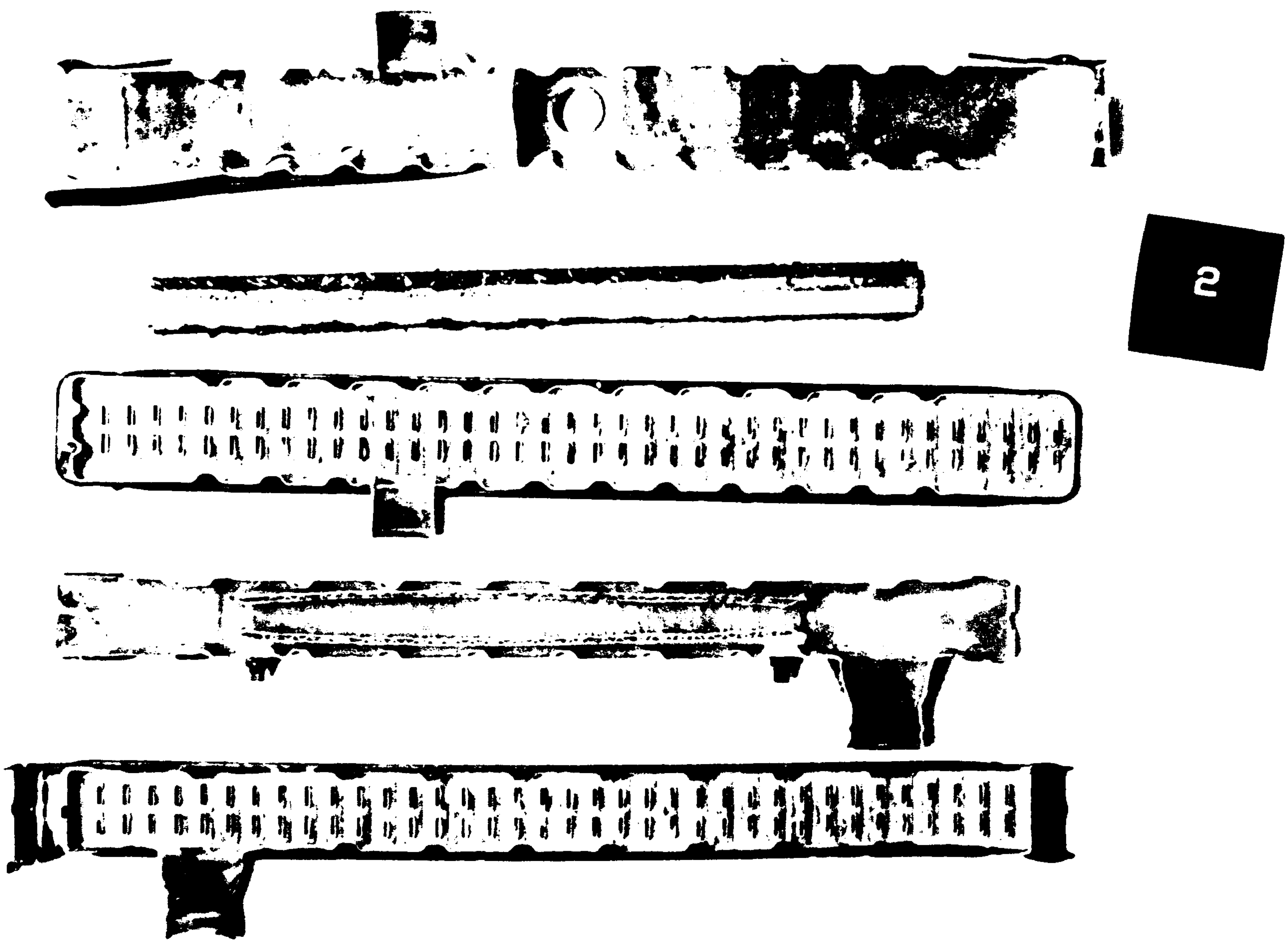

Figure C-26. Test No. 15. radiator's components.

Figure C-25. Test No. 15. aluminum pump.

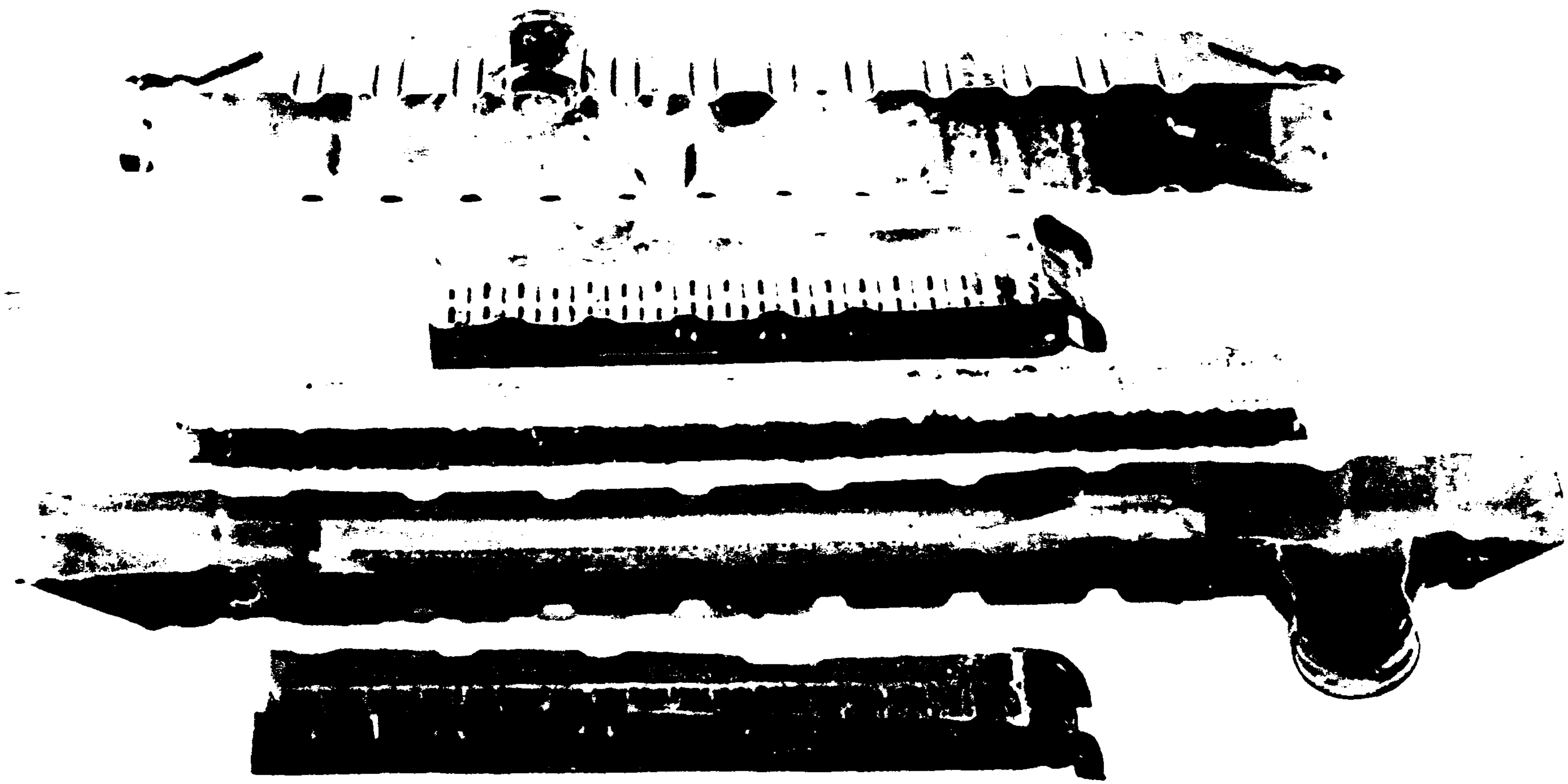

Figure C-24. Test No. 14. radiator's components.

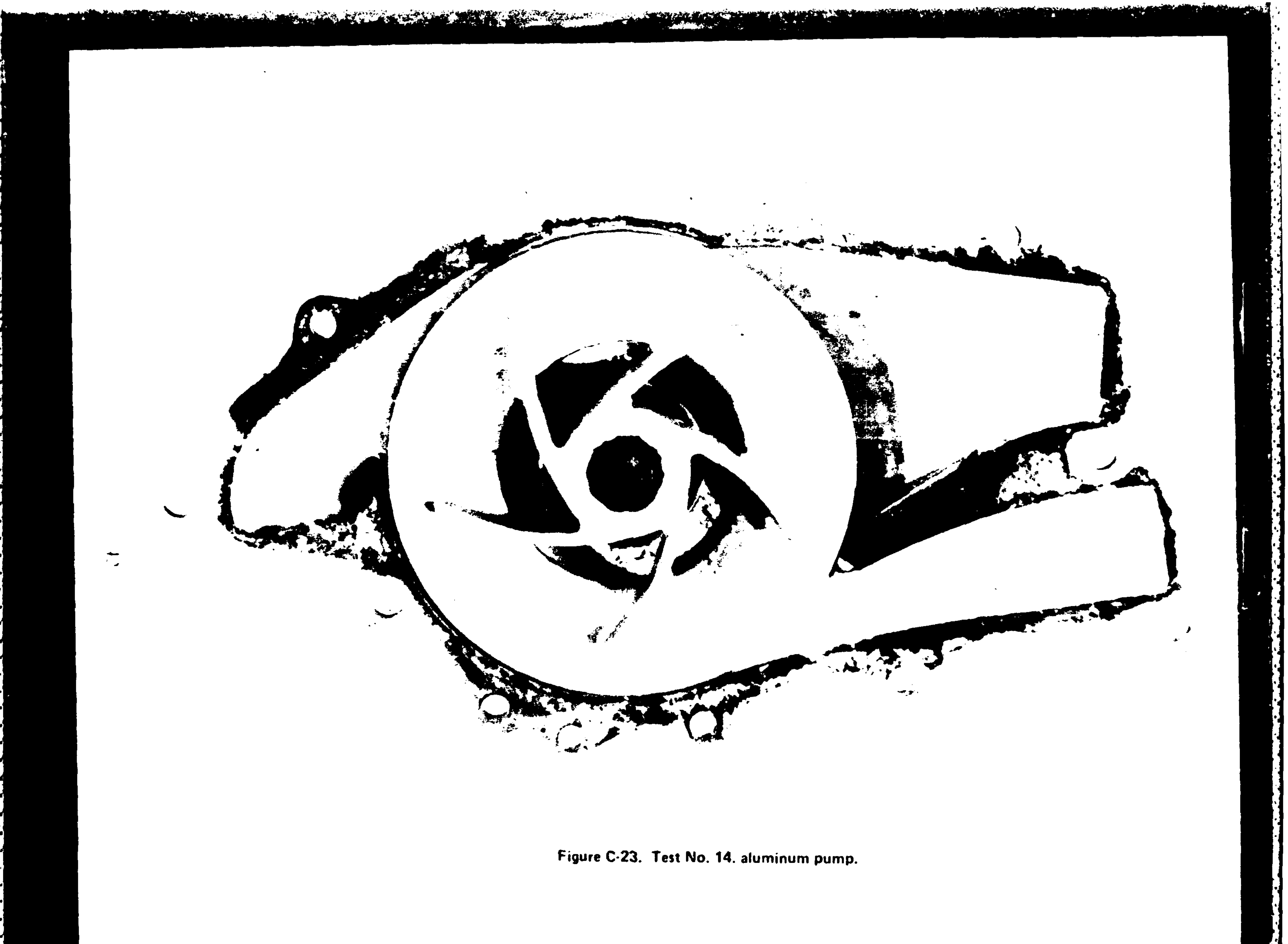

Figure C-23. Test No. 14. aluminum pump.

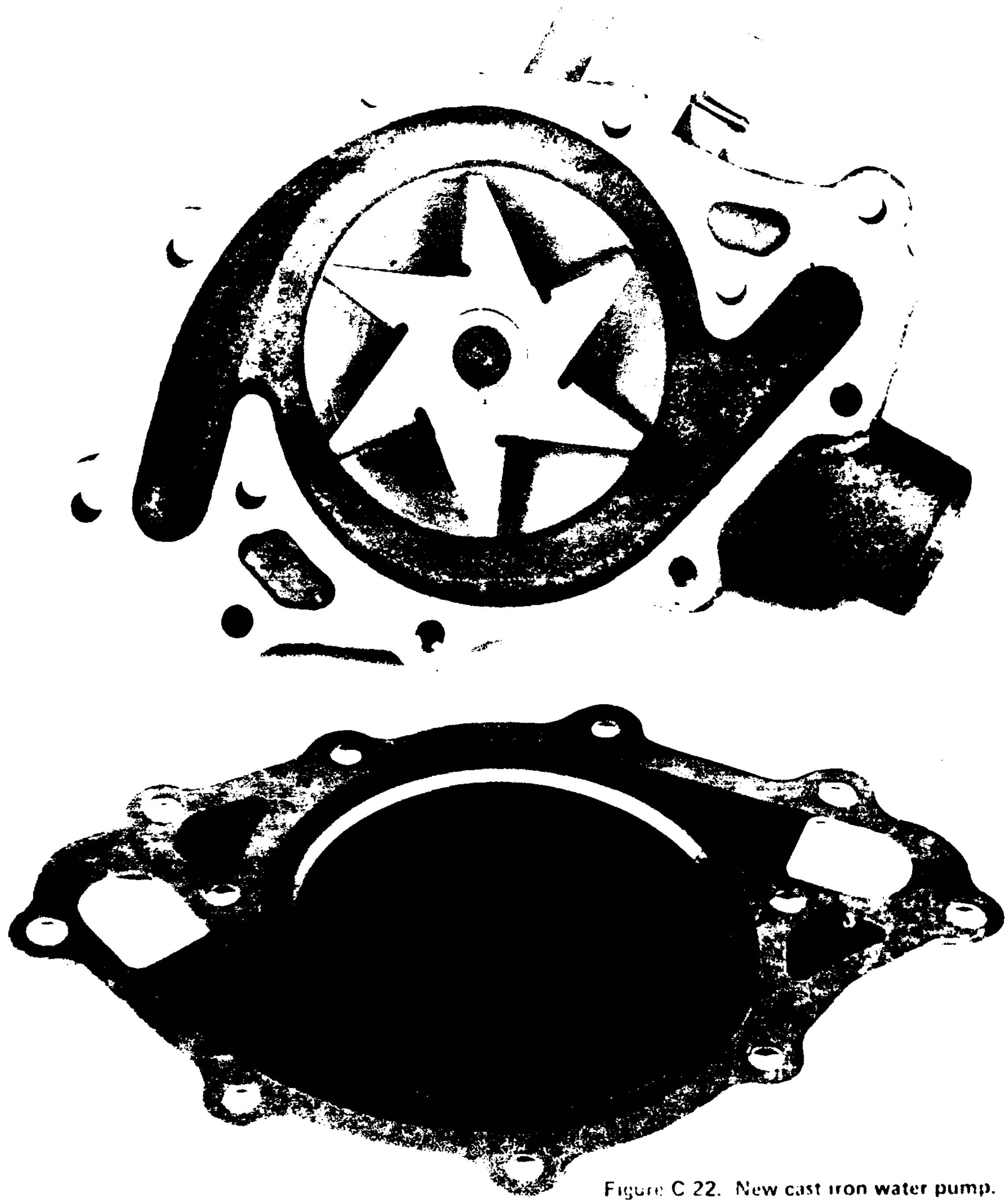

Figure C 22. New cast iron water pump.

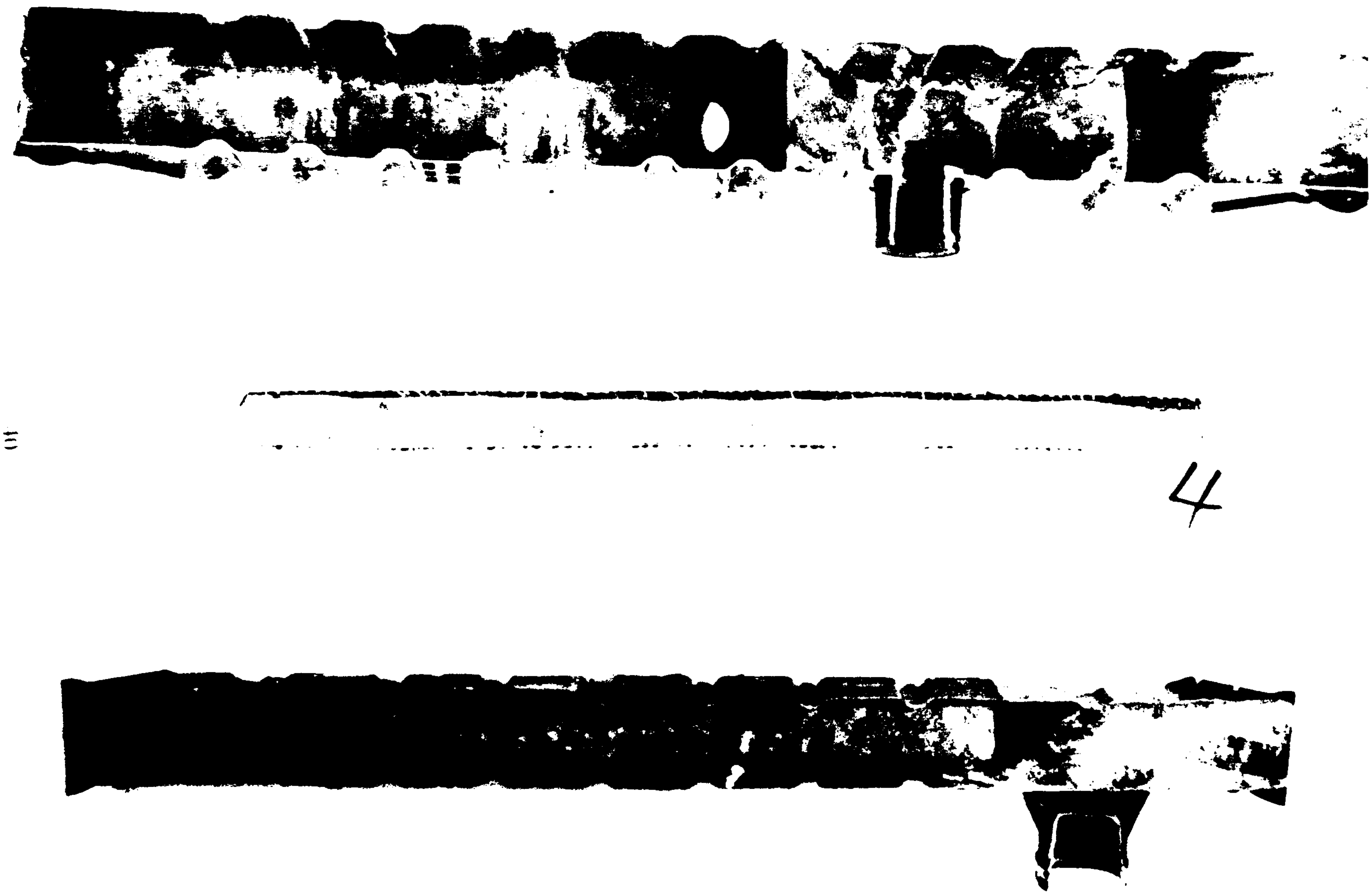

Figure C-21. Test No. 10. radiator's components.

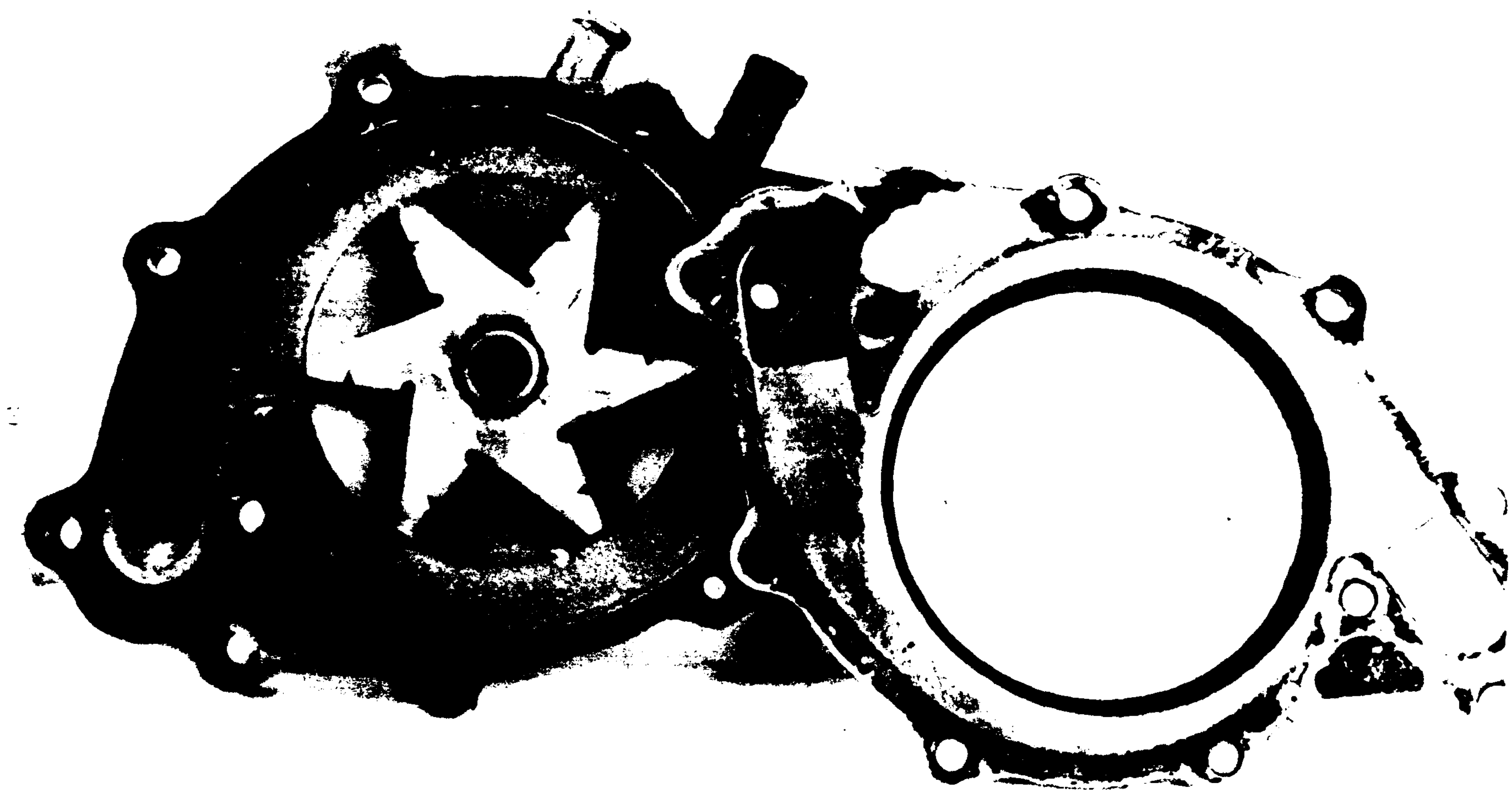

Figure C-20. Test No. 10. cast iron pump.

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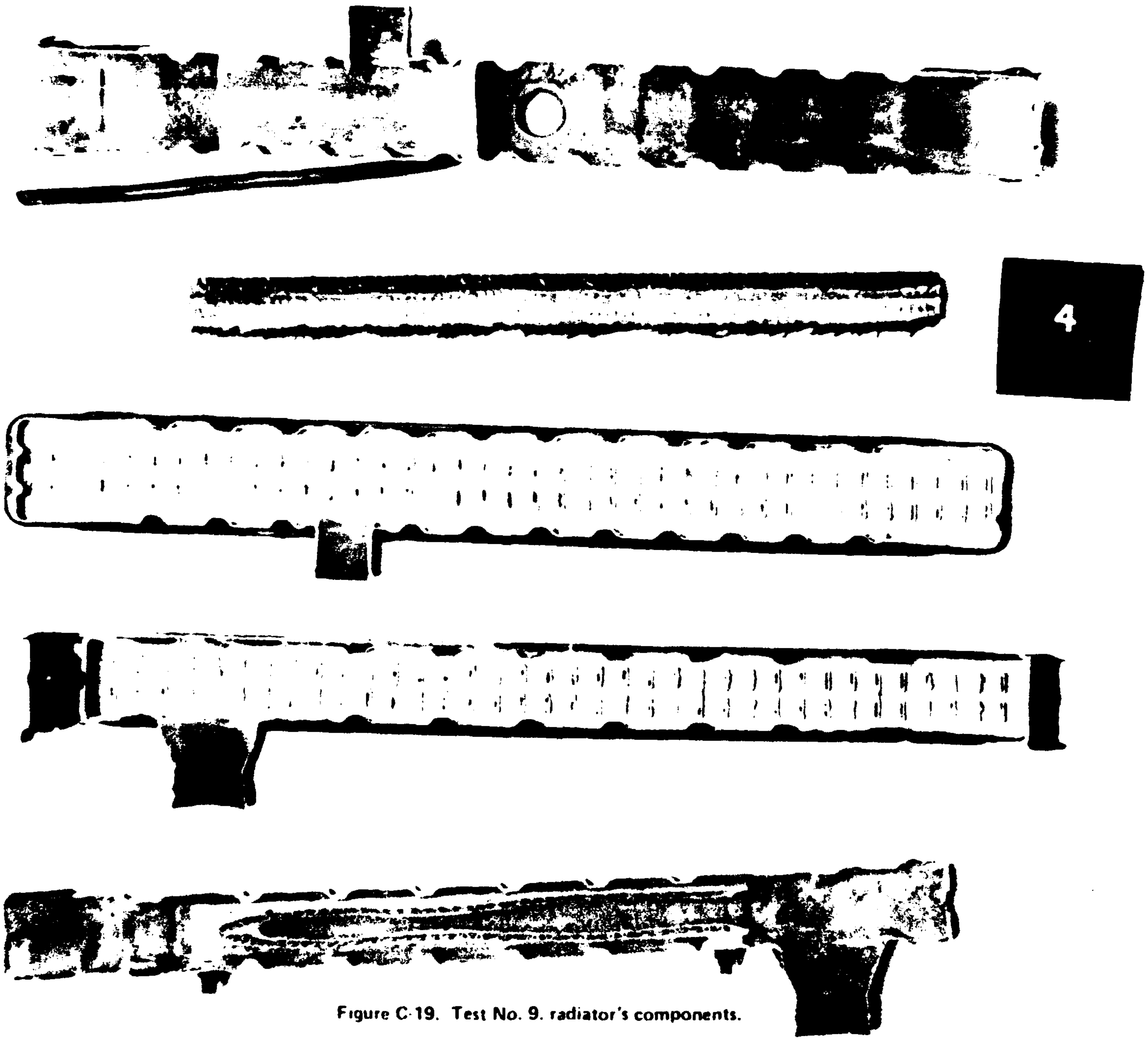

Figure C-19. Test No. 9. radiator's components.

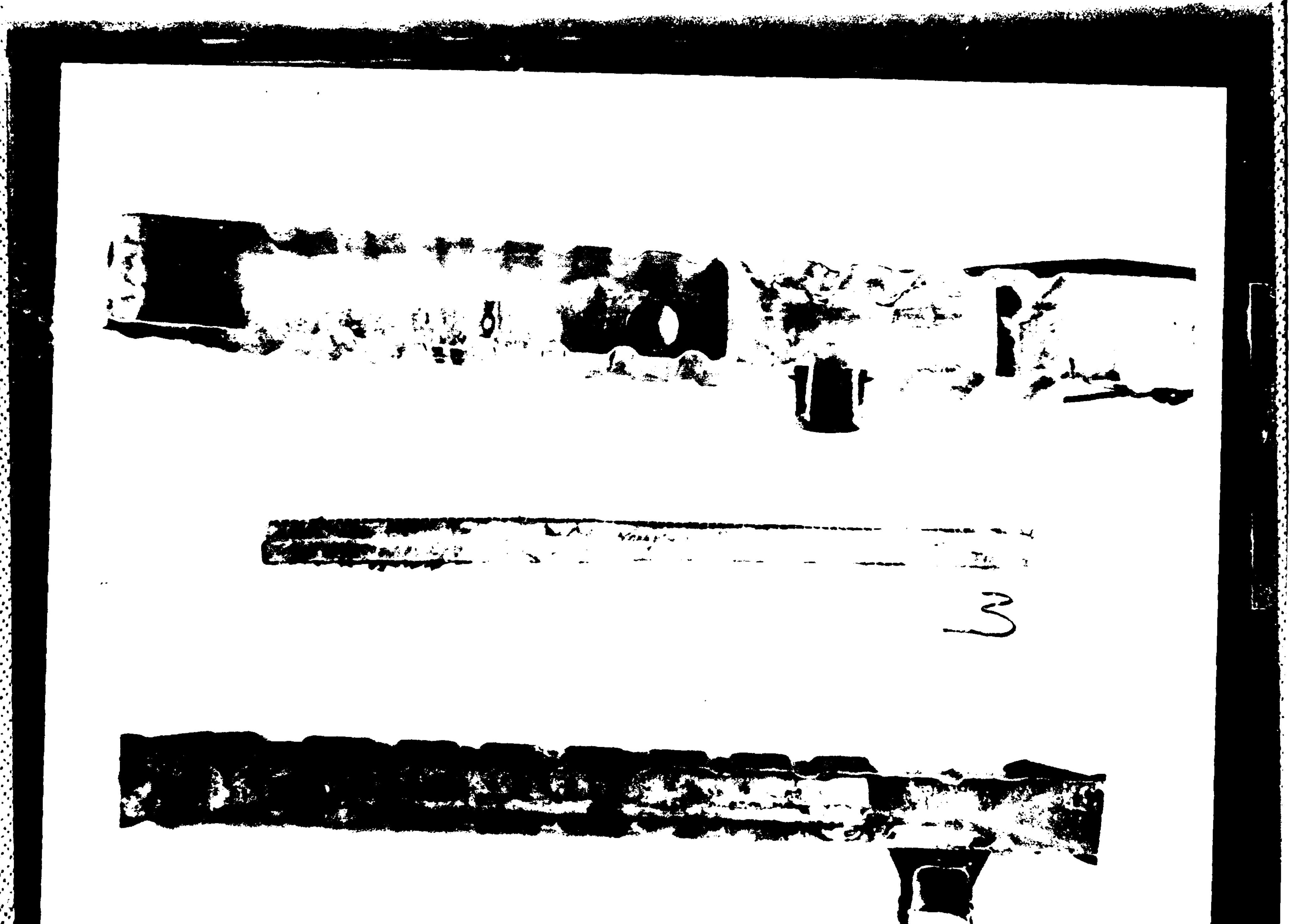

Figure C-18. Test No. 8. radiator's components.

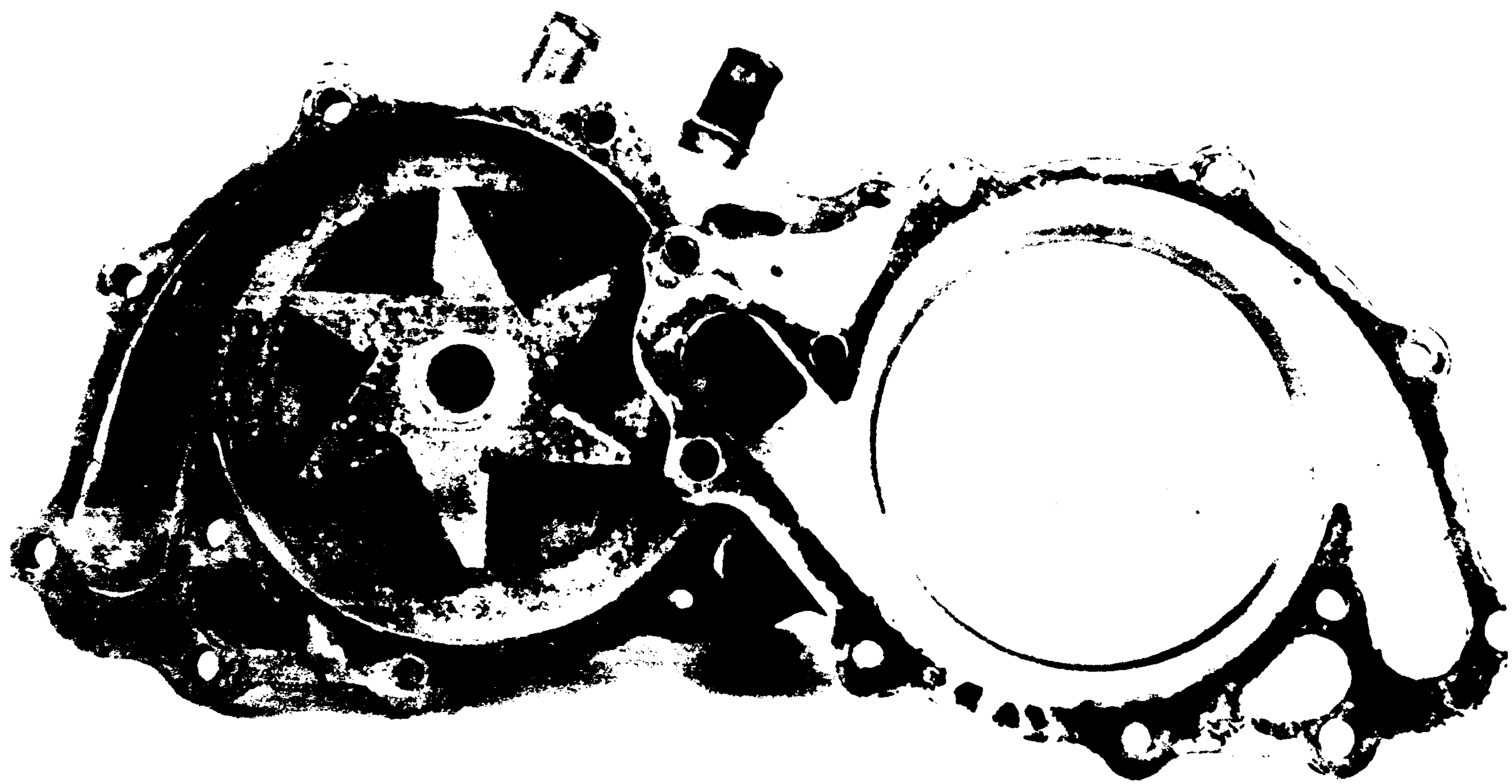

Figure C-17. Test No. 8. cast iron pump.

3

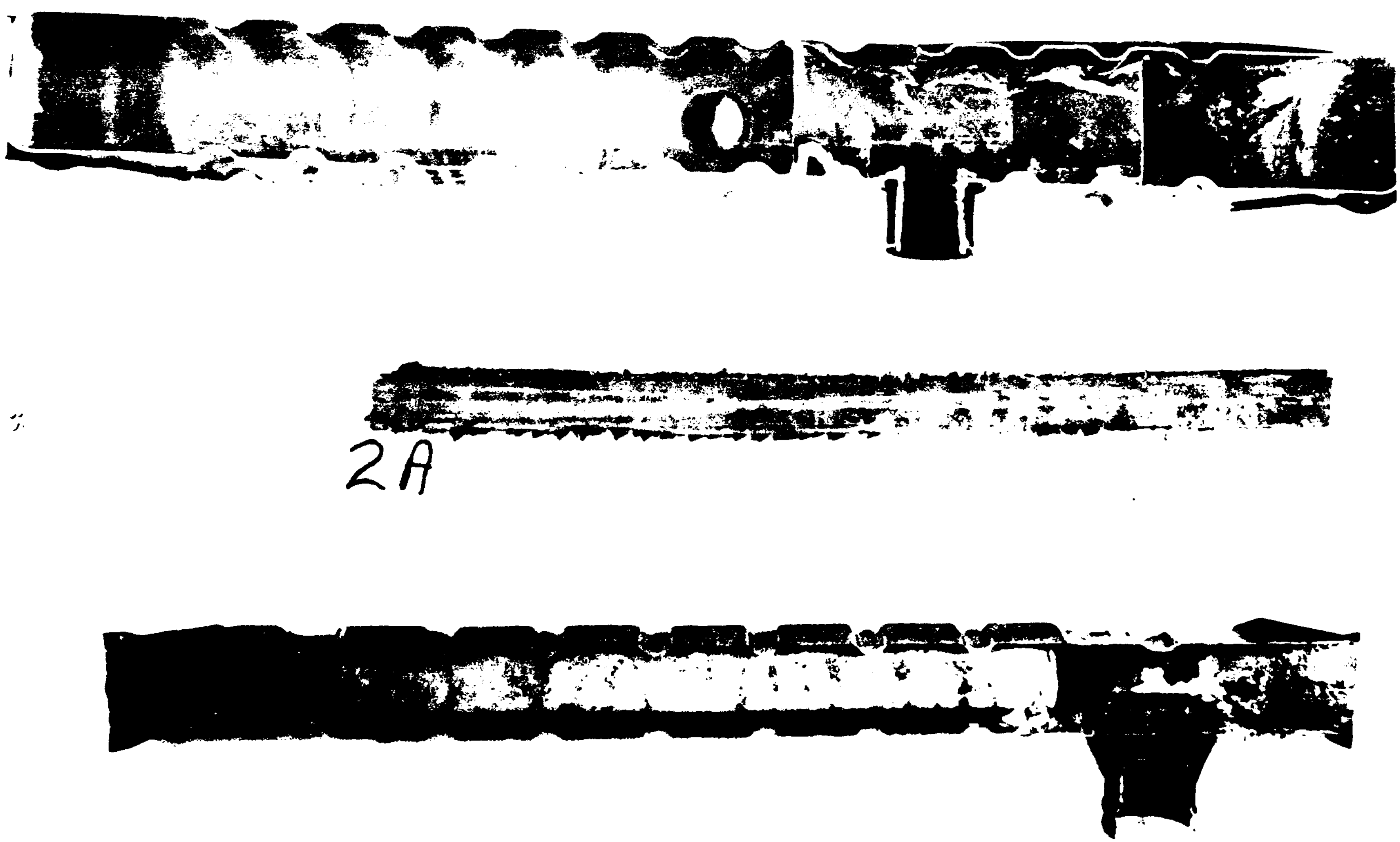

Figure C-16. Test No. 7. radiator's components, after 373 h.

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